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# Basic GIS terrain analysis methods for biophysical surveying of landscapes

Prepared by
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September 1997

for
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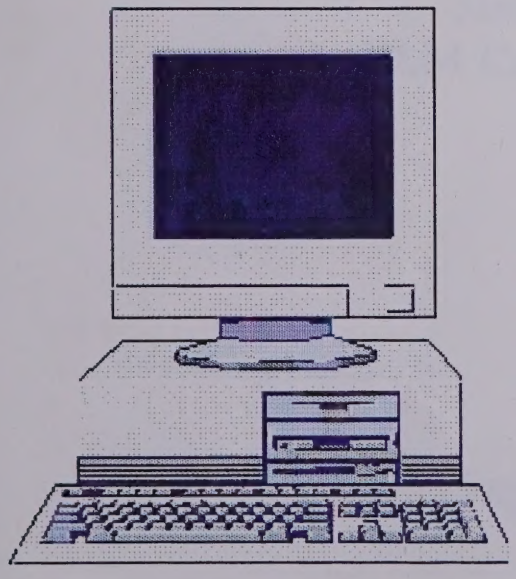

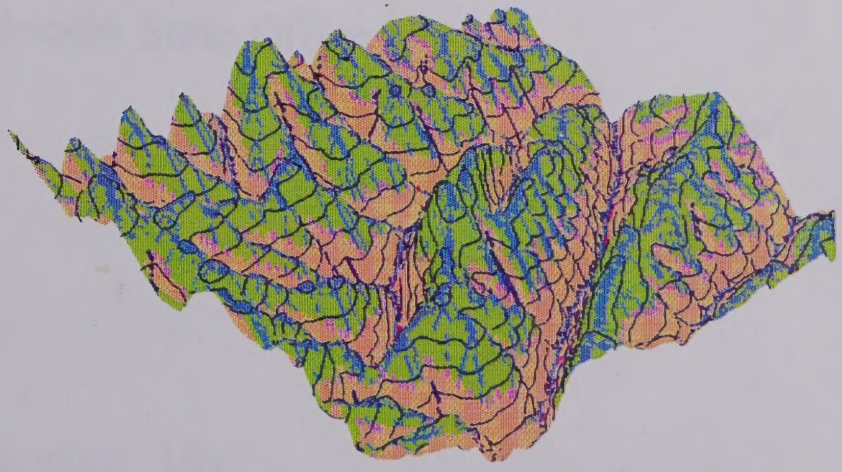

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## Introduction

When we first arrive in the mountains we might be impressed by their grandeur and sheer massiveness, but the next thing we observe are the drastic changes in climate as we continue to climb uphill. As we look more closely at the landscape we begin to notice the patterns of canyons and ridges, especially in the spring season when the canyons usually contain a roaring stream. If we stay in the mountains until the sunset and find ourselves in the long shadows in the valley we immediately experience the climatic differences between the areas that spend more time hidden in the shade than areas that spend more time exposed to sunlight. These examples are only some of the ways we directly experience terrain shape, beyond the sheer increase in effort needed to overcome gravity while walking up and down hilly landscapes. There are also many practical and aesthetic issues related to terrain morphology on the personal and societal level. Consideration where to build for better defense, where to place roads, being moved by the fantastic view of the landscape and concerned about how to maintain it are examples of these issue. On the most basic natural level changes in terrain morphology affect the spatial distribution of water, soils, vegetation, and micro-climatic patterns of any given area.

Influence of terrain shape on local ecosystem processes (physical, chemical, and biological) is primarily in how it affects the intake, transformation, storage, transport, and output of energy and matter within a given area, preferably an area where the locations of input and output are relatively easy to outline and the processes occur mostly within the area's boundary. Examples of inputs are the energy and mass input of flow of water from precipitation and the energy input of irradiation by sunlight. Terrain morphology controls to a large extent the distribution of surface water and the location and duration of sunshine and shade areas in relationship to the location of the sun in the sky. Terrain also can be said to contain its own energy, which is the potential energy related to the elevation of an object on the landscape and which is due to gravity, and the kinetic energy into which it potential energy can change when the object begins to move down the

landscape to a lower elevation. Storage of water and minerals in solution is also an aspect of the system. Water entering the subsurface layes can be temporarily stored in the soil before it exits into the groundwater, surface waters, and potentially even evapotranspiration as it is drawn back up through capillary action to the near surface, or, more commonly, is drawn up by roots of plants and then transpired into the atmosphere. The output processes therefore include evapotranspiration, exit of water out of the system via surface or subsurface outlets, and transfer of sediment with surface waters through sheet and rill, gully and channel sediment erosion and transport. All these processes are modified by the degree, shape and orientation of relief in the landscape.

The effects of the processes associated with changes in terrain morphology become attenuated as the degree of relief in the landscape decreases, but continue as long as there is some amount of it. Understanding this in a somewhat qualitative but common-sense way, the ease with which watershed networks can be delineated for any region generally reflects the degree of influence by terrain morphology on ecological processes. For example, in the coastal flatlands watershed boundaries sometimes have to be marked by the location of man-made levies, but in the Kansas rolling hill country watershed networks can be delineated with much greater ease and a good deal of clarity. While the effects of topography in Kansas are nowhere near as important as they are in the Rocky Mountains, they still play an influential role on physical and biological processes of the Kansas landscape.

Where there is some degree of terrain relief the flow of water tends to aggregate into natural networks. This can be observed at the site-scale watching how sheet flow becomes rivulets which join together creating miniature drainage networks and forming rills, channels, streams, and rivers, up to the continental scale. It is a property of irregular surfaces that flow will tend to aggregate into drainage networks seeking the path of least resistance across the landscape. Depending on the velocity of flow the resistance can be offered not only by the gross terrain shape but also by vegetation, rocks, and litter. In locations where we might see in the landscape an apparently large sheet flow of water it is because we are looking at large volumes of water being transferred within a nearly invisible wide and very gently sloped concavity, or there is an intersection of the surface and the groundwater table.

The surface drainage networks interact with subsurface flows which to some extent mimic the surface flow, but are also influenced by the properties of the soil and bedrock material. Although surface watershed boundaries do not strictly conform with subsurface flow watershed boundaries, there is generally a high degree of correlation. Taking this fact under consideration, as well as all the other requirements for a unit of landscape systems analysis, a watershed represents a natural areal unit for analysis of all landscapes that have some degree of relief. Such landscapes can be understood as consisting of three major categories of geomorphic form and processes associated with the form. They are divided by streams into *drainage networks* and show effects of the erosional and depositional processes within these networks. Each part of the drainage network can be assigned some topographic area where water generally flows to the same pour location, in other words terrain can be subdivided into *watershed* or *catchment* units of various order in a *hierarchical drainage network* with easily identifiable output locations for each system unit. The land areas between drainages are the *hillslopes* and *valley floors* and have their own sets of processes which result in a variety of landforms. The hillslope processes end at the lowest portion of the toe slope, or the limit of sediments deposited from the slopes. In the valleys fluvial processes are predominant. All these natural events are happening within the overall context of watersheds or catchment basins. As a fourth category one could also consider flatlands, but they will be considered here as special areas within the extent of drainage basins in hilly and mountaineous regions.

Classification of mountainous and hilly landscapes into the categories of hillslopes, drainages, and watersheds permits bringing together the disciplines of hillslope and fluvial geomorphic processes in the context of a unit which has both a geomorphic and hydrologic significance. A watershed is also a geographic system unit for application of system analysis principles to catchment properties within the framework of a hierarchical network where we can identify patterns of transport and spatial extent of processes. However, in recent literature there has been stress on the term "topographic watershed" as if it represents another category of a watershed different from others used by some researchers. Presumably a *topographic watershed* is one with clearly defined and identifiable divides that can be found in the field. Another way of looking at the term *topographic watershed* is to give it a probabilistic meaning, for example that at least 85% of the water needs to flow through the delineated catchment area toward its outlet location without crossing the delineated watershed boundaries to make it a genuine

topographic catchment. Although it hasn't yet been precisely determined whether mini-watersheds delineated using GIS capabilities from 30 meter DEMs all exhibit this property, this definition seems to permit an adequate amount of leeway in allowing 0-15% possible flow across the delineated watershed boundaries. It would take some very powerful effects of peculiar topographic features not picked up by terrain data, for example caused by some sort of undetected fractures or faults to produce greater flow across watershed boundaries. These effects can be important in some locations and need to be included in consideration of a watershed, but based on this definition it should be possible to locate watershed boundaries for most locations on hilly or mountaineous landscapes. The question becomes not whether there is a clear divide separating the units, but whether there is an adequate degree of confidence that flow of water is directed in the actual landscape in such a way that the delineated boundaries make sense.

From the point of view of this probabilistic definition, which also tries to include in its error range the possible effects of poor data resolution and surprises that can be discovered only through examination in the field, the watersheds delineated by GIS are accurate enough to serve as approximate boundaries of actual hydrologic system units. In GIS the criterion for delineating watershed boundaries is the direction of water flow as identified from DEM data of particular resolution. But in the context of the probabilistic definition, as long as the unit has no more than 15% flow across its boundaries, such a unit can be considered as genuinely a topographic watershed as the watersheds delineated by the continental divide. However even within this relatively safe range thorough work requires some actual groundtruthing in the field or some sort of comparison with more accurate data, if such are available.

A relatively easy way to semi-quantitatively evaluate the accuracy of watershed delineation is based on comparison of stream data for the project area obtained from two different sources. Since the GIS watershed delineation programs also delineate flowpaths as an important component of their processing, it is possible to model drainage networks from digital elevation data. At the same time much of the country is covered with rather accurate (to few meters) USGS digital line graph (DLG) data which show locations of surveyed streams. Overlaying DLG data on top of modeled drainage data shows rather clearly the degree of accuracy of the model. Most of the maps included in this report will show both types of data displayed for the readers' comparison. The primary problem with generating

accurate drainage or divide data lie in the fact that the hydrologic terrain analysis software has difficulty in calculating flowpaths within flat regions. This problem with automated flowpath and watershed boundary delineation is difficult to overcome since in flat areas many other factors, such as vegetation, control direction of the flow of water besides gross terrain morphology. However similar difficulties would arise for a hydrologist trying to define flowpaths from 7.5 minute USGS topographic sheet which is similar in accuracy to the 30 m resolution DEM.

Another argument for using GIS automated watershed delineation methods (assuming the need of correction of the data for very flat areas), besides the fact that they are quick and add a lot of flexibility to our analysis, is that the 1:24000 USGS topographic maps that are used for most manual watershed delineation provide only a little more information about elevations than the 30 meter DEMs. Unless the DEMs contain gross errors, which usually becomes apparent in terrain analysis processing, the automated processing permits an impartial and repetitive method for analyzing terrain flow boundaries.

To summarize the arguments of the introduction, it is proposed that most landscapes that contain variety in topographic relief are naturally subdivided by drainages to form *drainage network patterns* and *hillslopes* between the drainages. Patterning of flow into networks can be observed from microscopic to macroscopic scales. Portions of these networks are fed by different regions of the landscapes, areas which form *catchments*[1] for the flow. These catchments can be delineated using GIS methods on DEM data to the degree of accuracy based on a working assumption that 85% of the actual surface flow located within the delineated boundaries does actually occur there, so that the topographic division of flow is genuine. Further working assumption is that, even assuming the inaccuracy of DEM data, mini-catchments of more than fifty acres in size can be adequately delineated using automated means for hilly and mountainous landscapes.

The following report will concentrate primarily on the *hillslope* aspect of terrain morphology. Future reports will also describe the GIS modeling analysis, and interpretation of *drainage pattern* and *watershed* morphology and it's relationship to physical and biological processes on the landscape.

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[1] watersheds, erosional basins, basins, hydrologic units, mini-watersheds, mini-basins, sub-watersheds

## 2. Automated mapping of hillslope morphology

All slopes can be considered to consist of convex, concave, and flat slope facets. Ruhe (1975) identifies nine basic geometric forms of hillslopes, as depicted in figure 1.

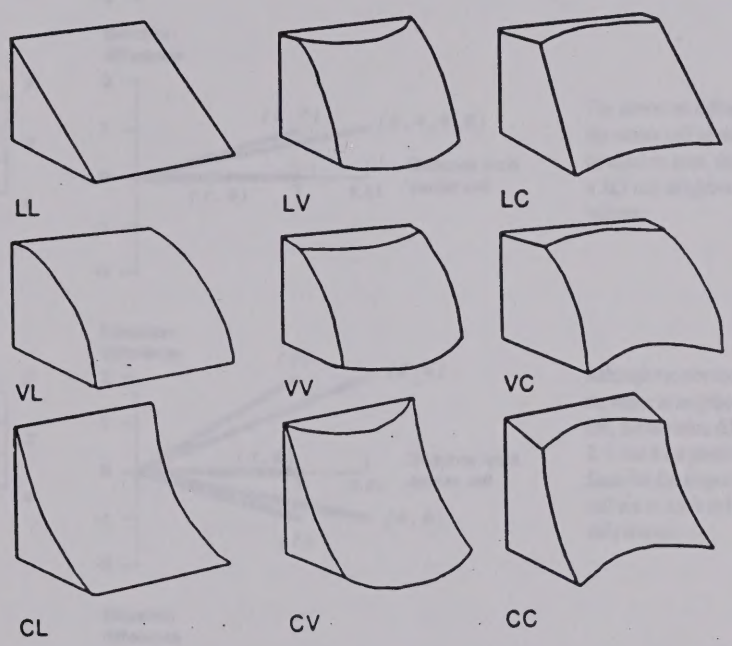



Figure 1. Geometric forms of hillslopes. **L** is linear, **V** is convex, **C** is concave (Ruhe, 1975).

Based in part on Ruhe's concept of nine representative combinations of concave-convex relationships, using a *neighborhood* or *focal* approach to analyse the terrain surface, a neighborhood curvature analysis methodology has been developed (Blaszczynski, 1997). The technique averages the positive and negative slopes within the neighborhood to produce an average positive or negative slope value that indicates tendency toward convexity or concavity within the focal area. Calculated in this way the combinations of concave and convex curvatures for a portion of the slope fall very much into the categories identified by Ruhe. Figure 2 on the next page shows the way average slope values are calculated within a 3x3 cell neighborhood.

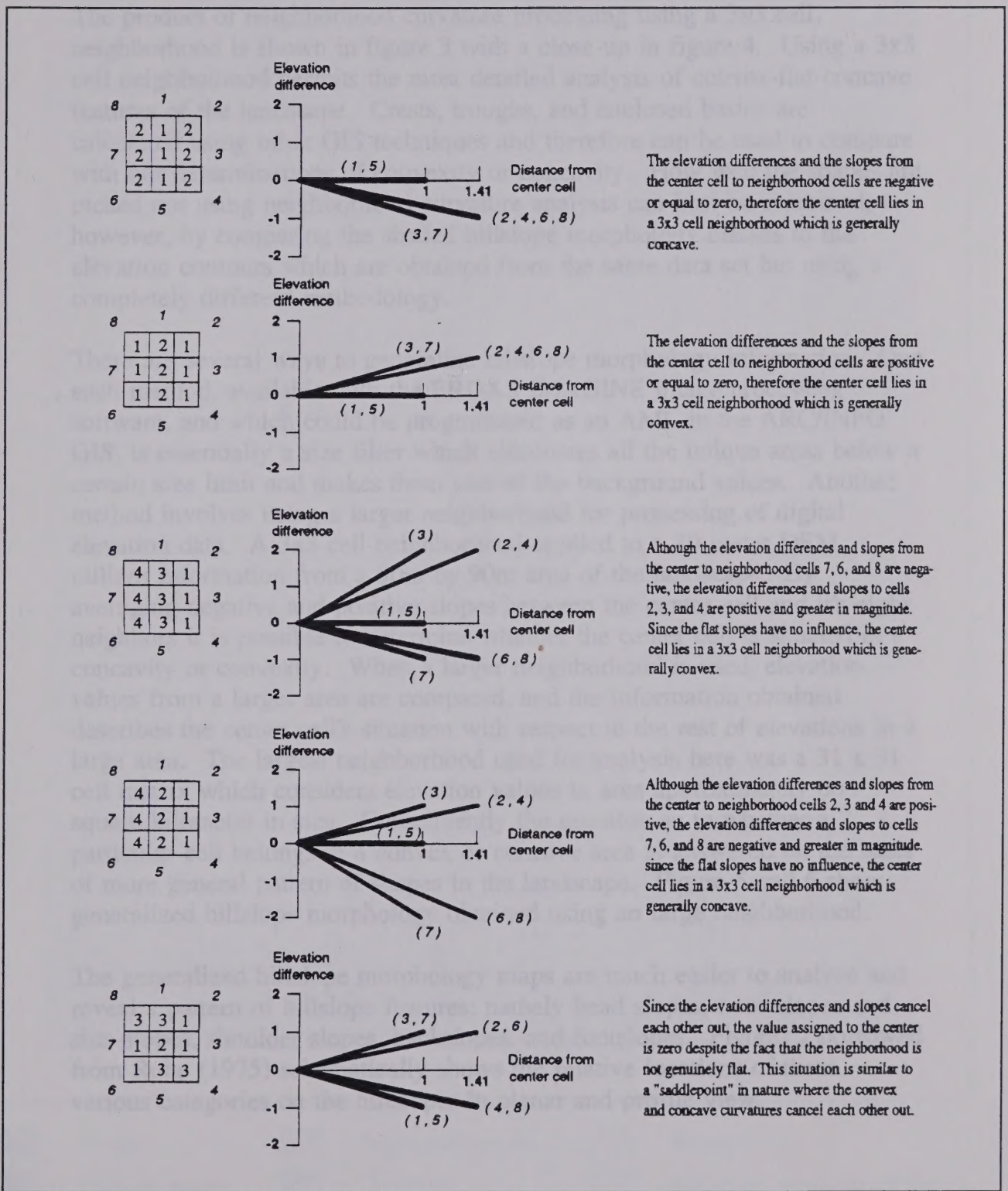
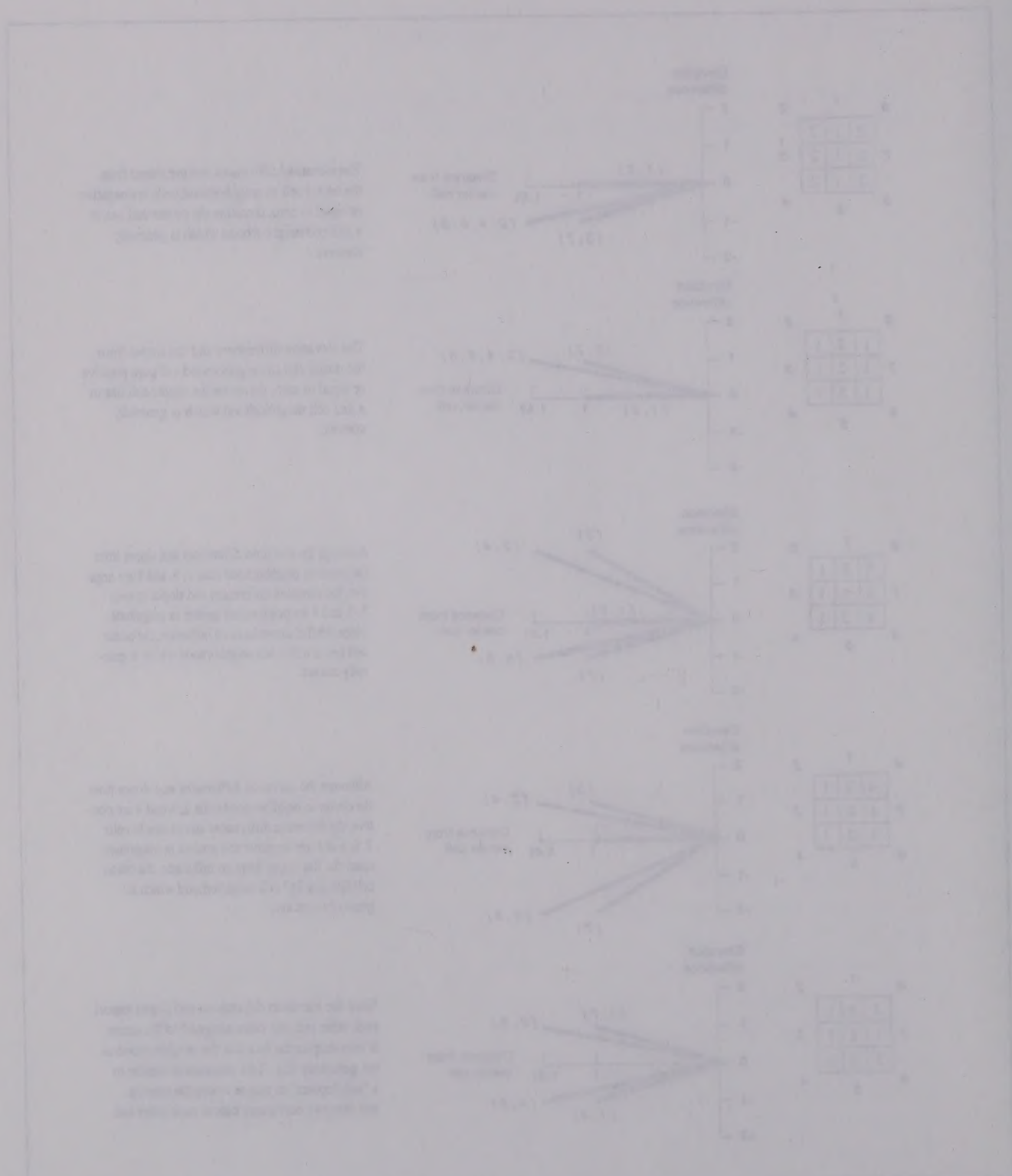

Elevation difference
Distance from center cell
(1,5)
(2,4,6,8)
(3,7)
The elevation differences and the slopes from the center cell to neighborhood cells are negative or equal to zero, therefore the center cell lies in a 3x3 cell neighborhood which is generally concave.
Elevation difference
Distance from center cell
(3,7)
(2,4,6,8)
(1,5)
The elevation differences and the slopes from the center cell to neighborhood cells are positive or equal to zero, therefore the center cell lies in a 3x3 cell neighborhood which is generally convex.
Elevation difference
Distance from center cell
(3)
(2,4)
(1,5)
(6,8)
(7)
Although the elevation differences and slopes from the center to neighborhood cells 7, 6, and 8 are negative, the elevation differences and slopes to cells 2, 3, and 4 are positive and greater in magnitude. Since the flat slopes have no influence, the center cell lies in a 3x3 cell neighborhood which is generally convex.
Elevation difference
Distance from center cell
(3)
(2,4)
(1,5)
(6,8)
(7)
Although the elevation differences and slopes from the center to neighborhood cells 2, 3 and 4 are positive, the elevation differences and slopes to cells 7, 6, and 8 are negative and greater in magnitude. since the flat slopes have no influence, the center cell lies in a 3x3 cell neighborhood which is generally concave.
Elevation difference
Distance from center cell
(3,7)
(2,6)
(1,5)
(4,8)
Since the elevation differences and slopes cancel each other out, the value assigned to the center is zero despite the fact that the neighborhood is not genuinely flat. This situation is similar to a "saddlepoint" in nature where the convex and concave curvatures cancel each other out.

Figure 2. A graph depicting five different combinations of elevation values within a 3- by 3-cell neighborhood and vectors representing negative, positive, and zero value slopes between the center and neighborhood cells.

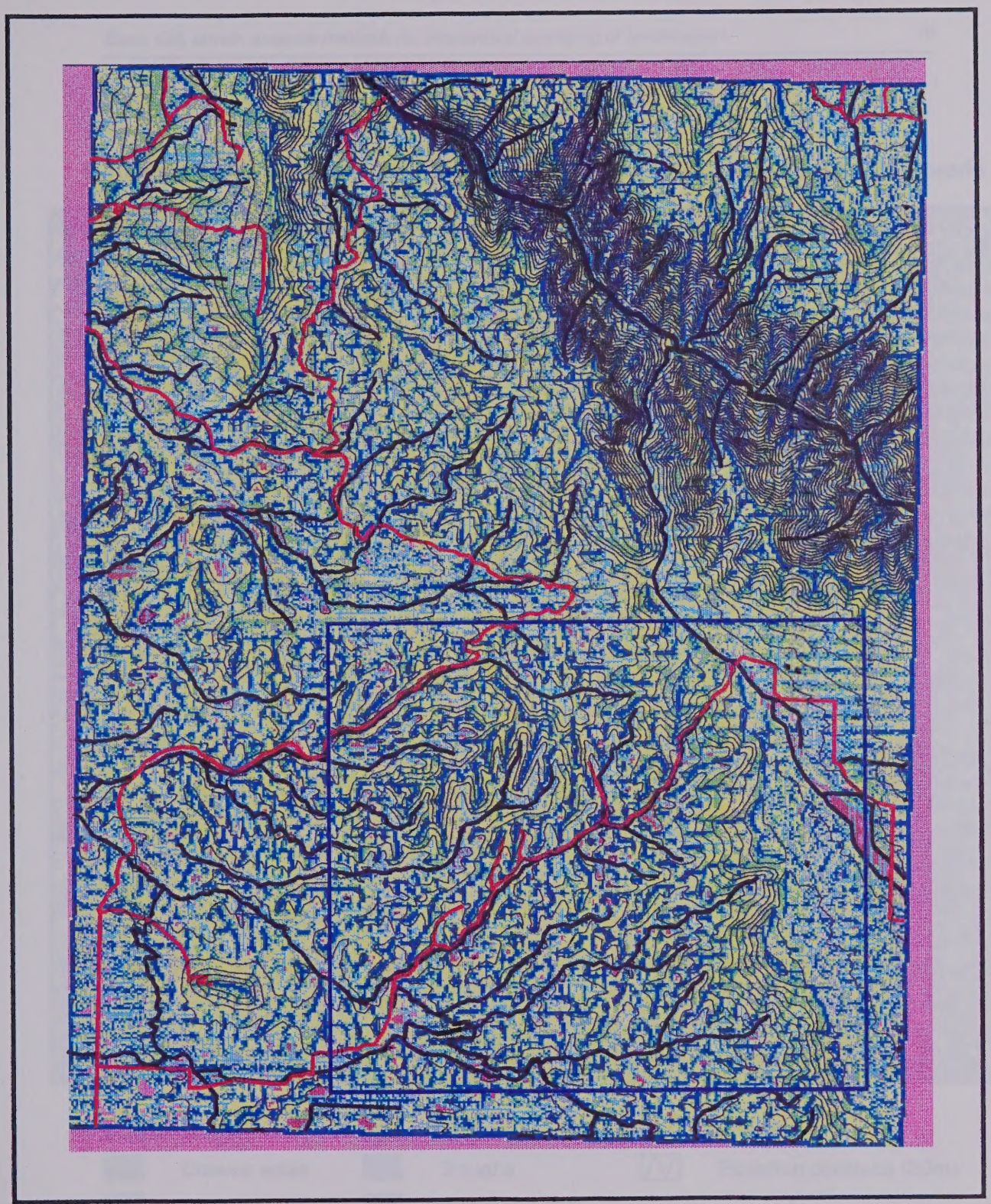


The product of neighborhood curvature processing using a 3x3 cell neighborhood is shown in figure 3 with a close-up in figure 4. Using a 3x3 cell neighborhood permits the most detailed analysis of convex-flat-concave features of the landscape. Crests, troughs, and enclosed basins are calculated using other GIS techniques and therefore can be used to compare with our determinations of convexity or concavity. How well the shapes are picked out using neighborhood curvature analysis can best be examined, however, by comparing the shaded hillslope morphology classes to the elevation contours which are obtained from the same data set but using a completely different methodology.

There are several ways to generalize hillslope morphology information. One such method, available with the ERDAS IMAGINE image processing software, and which could be programmed as an AML in the ARC/INFO GIS, is essentially a size filter which eliminates all the unique areas below a certain size limit and makes them part of the background values. Another method involves using a larger neighborhood for processing of digital elevation data. A 3x3 cell neighborhood applied to a 30 meter DEM utilizes information from a 90m by 90m area of the landscape. By averaging negative and positive slopes between the center cell and it's eight neighbors it is possible to determine whether the center cell is situated in a concavity or convexity. When a larger neighborhood is used, elevation values from a larger area are compared, and the information obtained describes the center cell's situation with respect to the rest of elevations in a large area. The largest neighborhood used for analysis here was a 31 x 31 cell matrix which considers elevation values in area approximately one square kilometer in size. Consequently the question as to whether a particular cell belongs in a convex or concave area is answered on the basis of more general pattern of shapes in the landscape. Figure 5 and 6 show generalized hillslope morphology obtained using an large neighborhood.

The generalized hillslope morphology maps are much easier to analyze and reveal a pattern of hillslope features: namely head slopes, nose slopes and side-slopes, shoulder slopes, backslopes, and footslopes. Figure 7 borrowed from Ruhe (1975) schematically shows the relative locations of these various categories on the hillslopes in planar and profile view.

Detailed hillslope morphology map, Red Rock Canyon quad., Colorado



Crests
Convex areas
Sloping flats
Concave areas
Enclosed basins
Troughs
Horizontal flats
DLG stream data
Roads
Elevation contours (30m)

Figure 3. Detailed hillslope morphology map made using a 3- x 3-cell neighborhood.

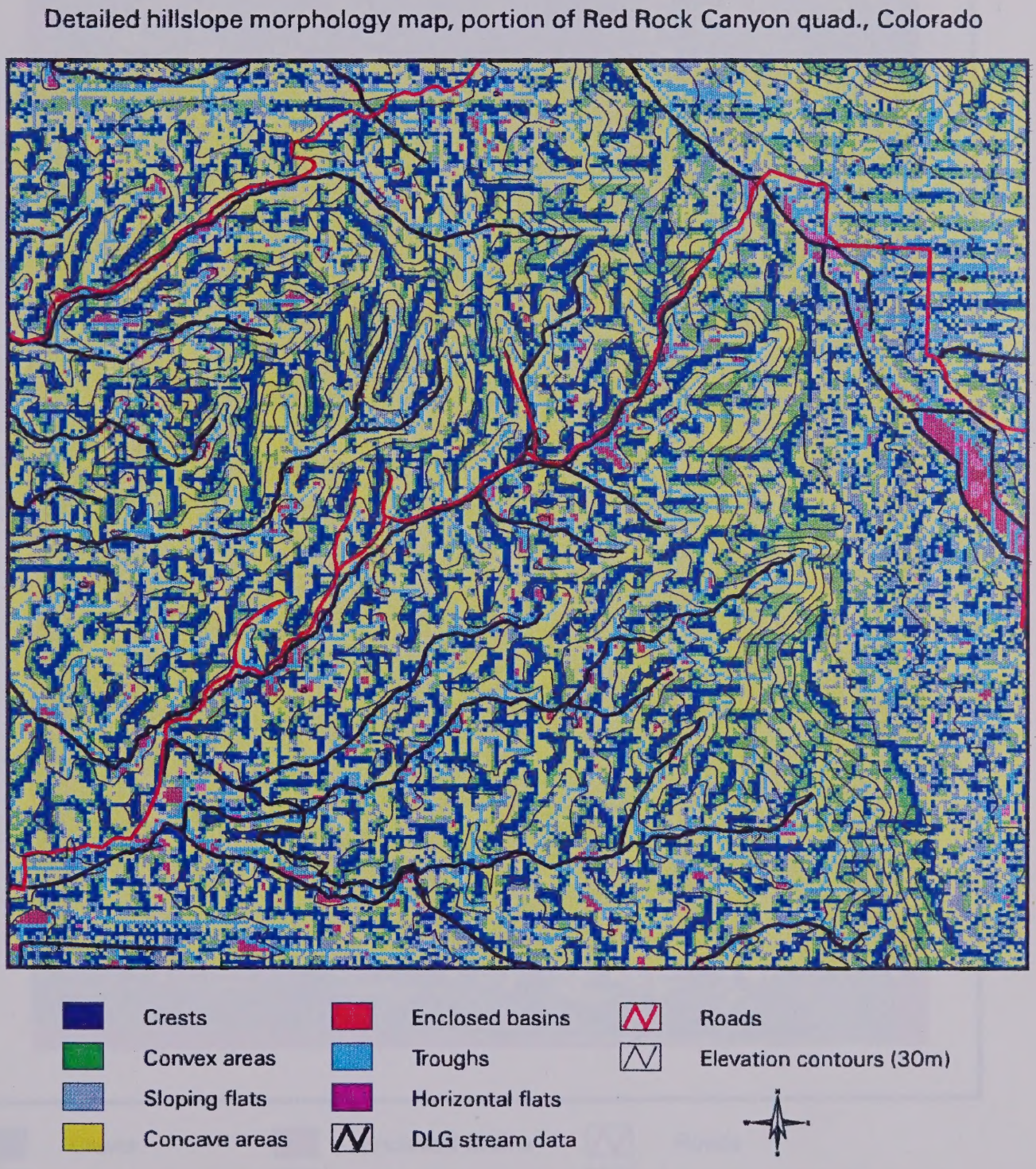



Figure 4. A close-up view of the detailed hillslope morphology map.

Generalized hillslope morphology map, Red Rock Canyon quad., Colorado

Crests
Convex areas
Sloping flats
Concave areas
Enclosed basins
Troughs
Horizontal flats
DLG stream data
Roads
Elevation contours (30m)

Figure 5. A generalized hillslope morphology map made using 31- 31-cell matrix.

Generalized hillslope morphology map, portion of Red Rock Canyon quad., Colorado

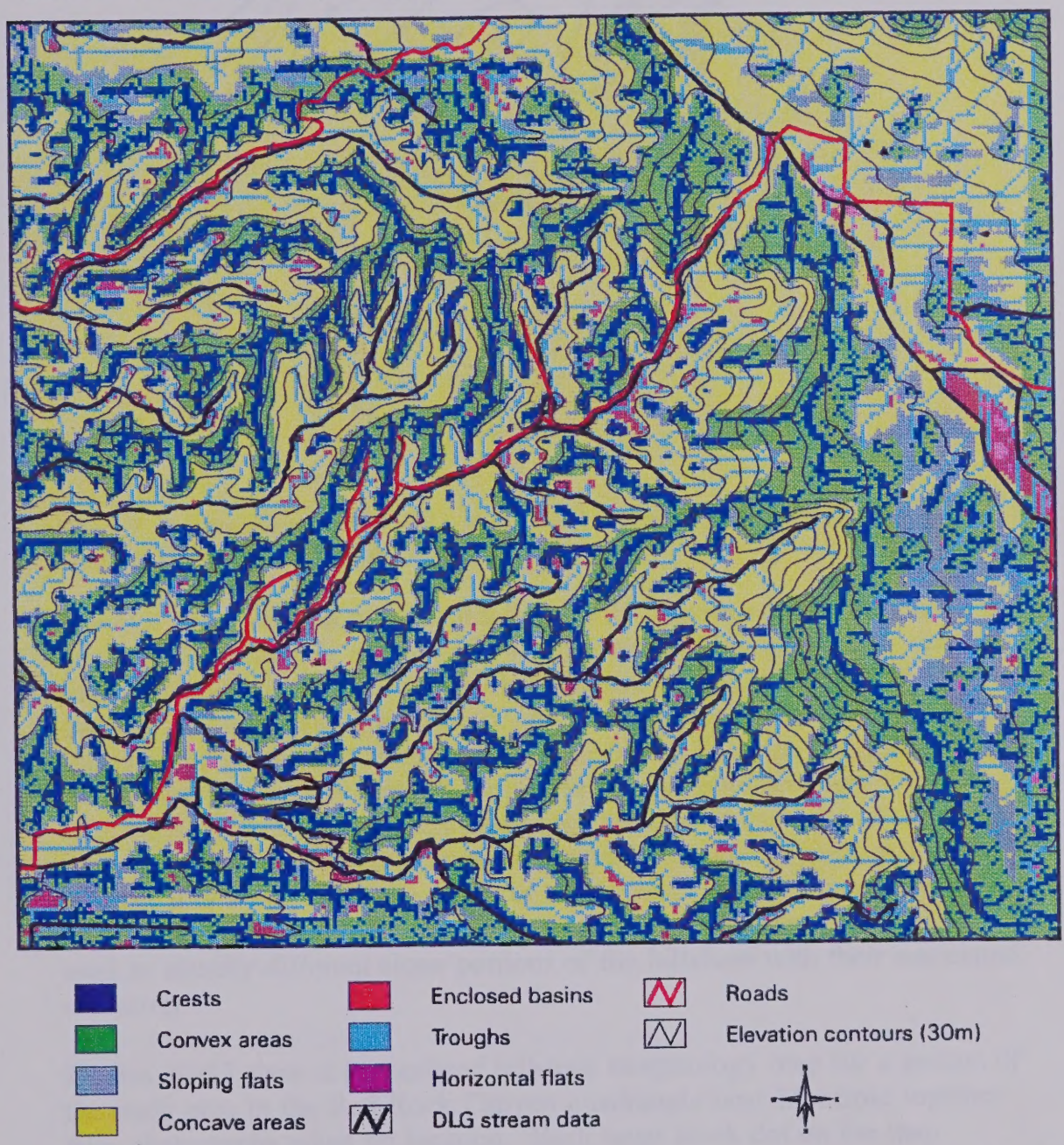



Figure 6. A close-up view of the generalized hillslope morphology map.

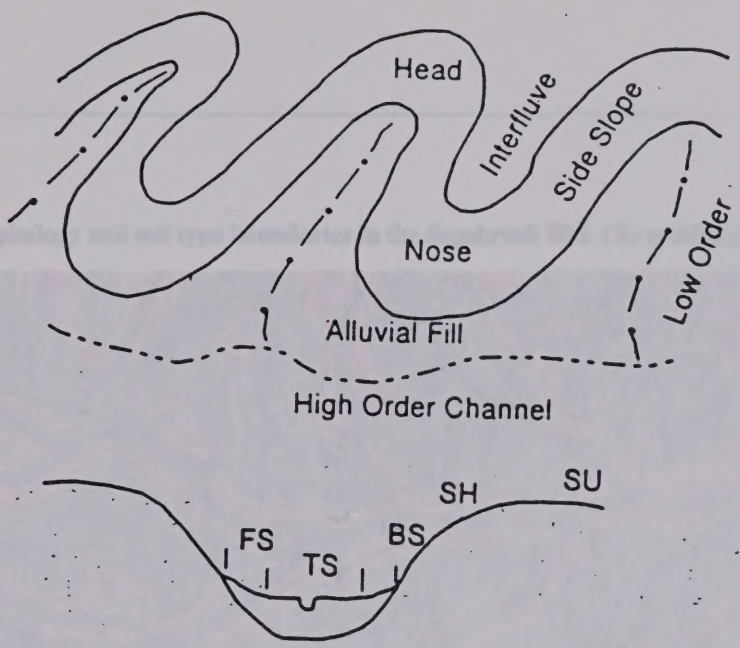
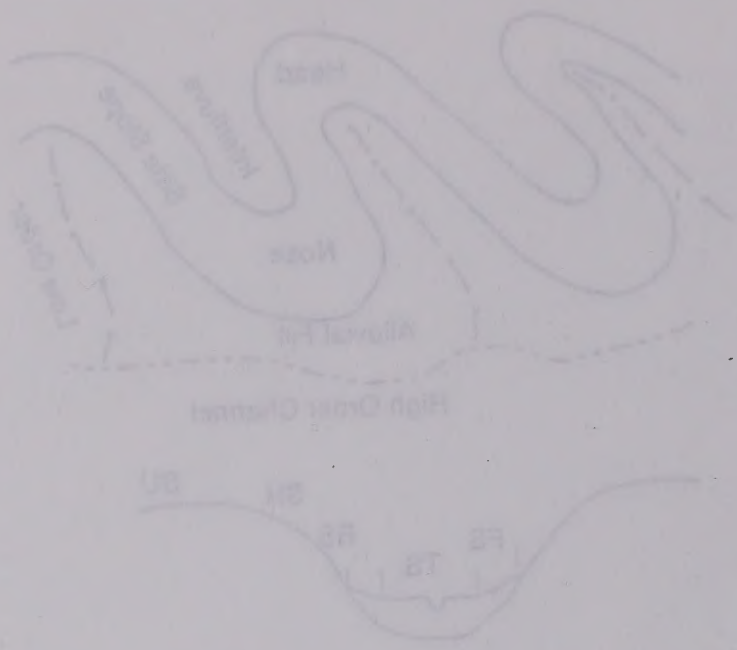



Figure 7. Landscape elements. **SU** = summit, **SH** = shoulder, **BS** = backslope, **TS** = toeslope, **FS** = footslope (Ruhe, 1975).

Figure 8 and 9 show a portion of a data set for Sagebrush Hill, another 7.5-min USGS quadrangle in Colorado which was used because a very complete data set is available for it. Figure 8 shows soil mapping units for the area overlaid on the generalized hillslope morphology map. Figure 9 shows the soil units again, but this time over the generalized hillslope morphology map which was broken into slope classes. The map is therefore more informative than a mere slope classes map because it also tells us whether a particular class in a generally convex or generally concave area, and whether it is a portion of the upper or of the lower slope. Potentially a combined generalized hillslope morphology and slope class maps can be used to identify different slope portions of the hillslope with their associated soil cover.

Figures 10-13 show a generalized hillslope morphology map for a section of the study area in the Red Rock Canyon quadrangle near Montrose together with photographs taken on location. Each large black dot on the map represents a GPS location where the photographs were taken by pointing the camera in different cardinal directions. Figure 10 shows the close-up of the morphology map with GPS sites and a road plotted on it, while Figure 11 shows photographs related to GPS site 9, Figure 11 to GPS site 10, and Figure 12 to GPS site 11. Landforms seen from the GPS locations are marked both on the map and on the photographs.



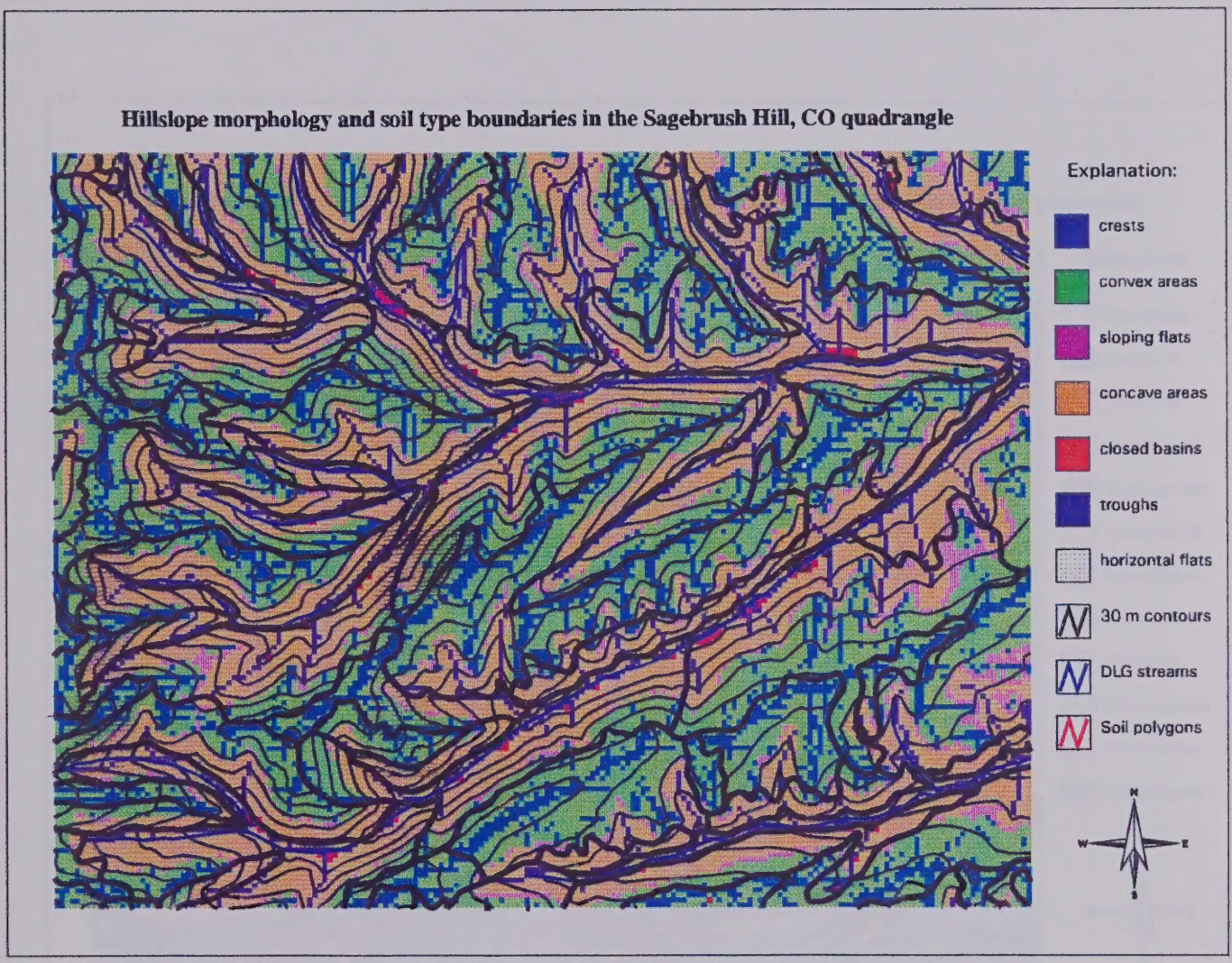



**Figure 8.** Generalized hillslope morphology and soil unit boundaries for a portion of Sagebrush Hill quadrangle, Colorado.

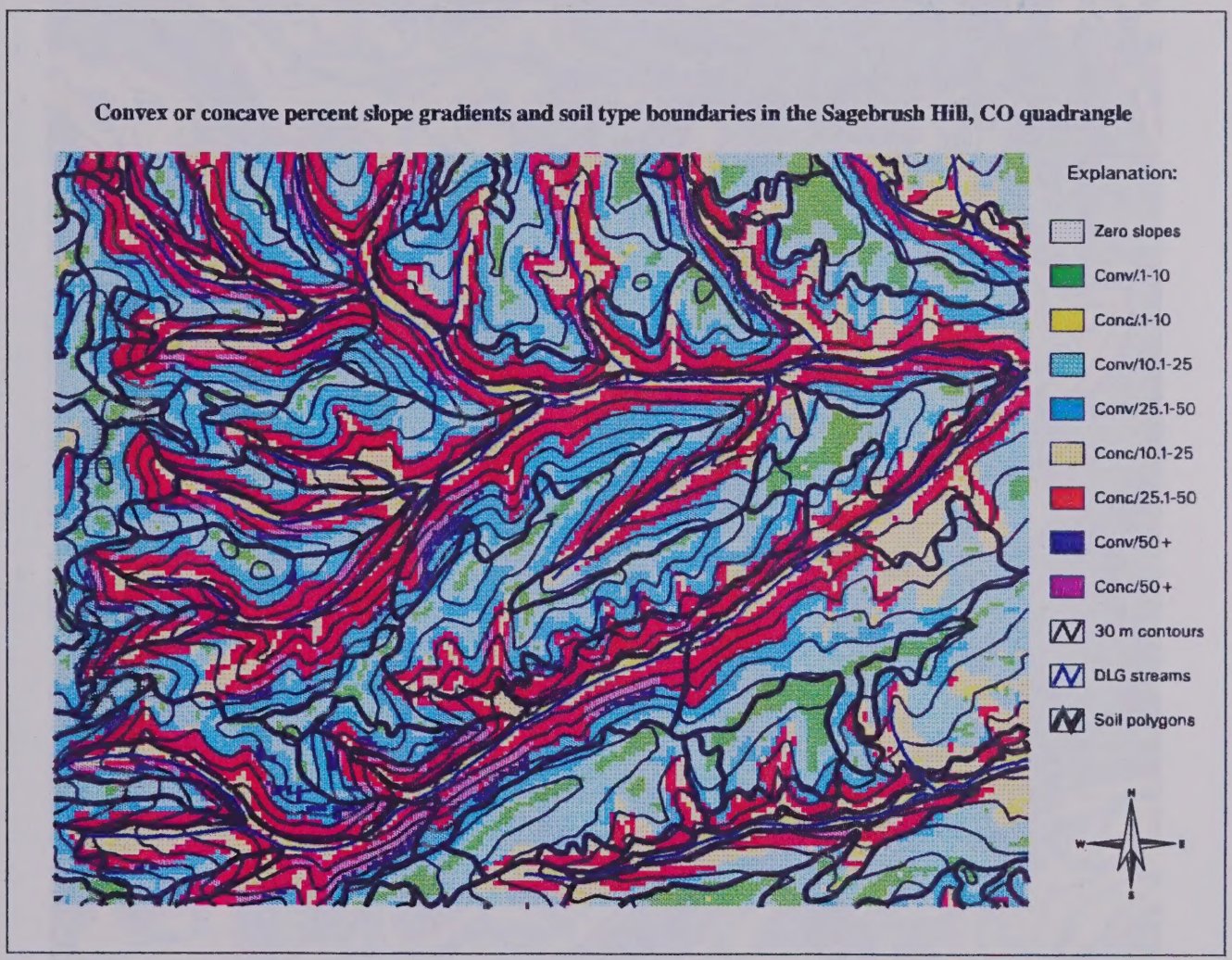
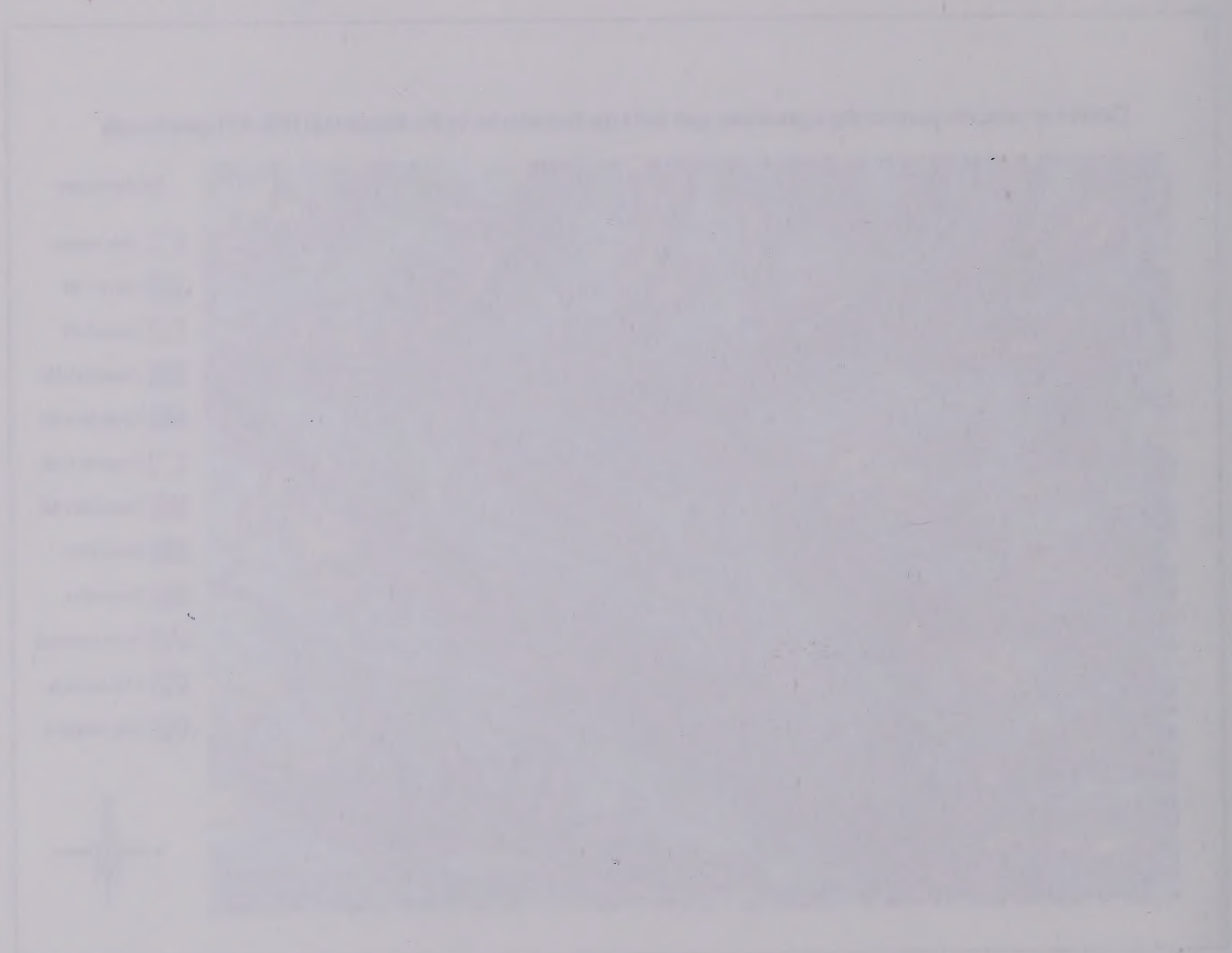



**Figure 9.** Generalized hillslope morphology, slope classes, and soil unit boundaries for a portion of Sagebrush Hill quadrangle, Colorado.



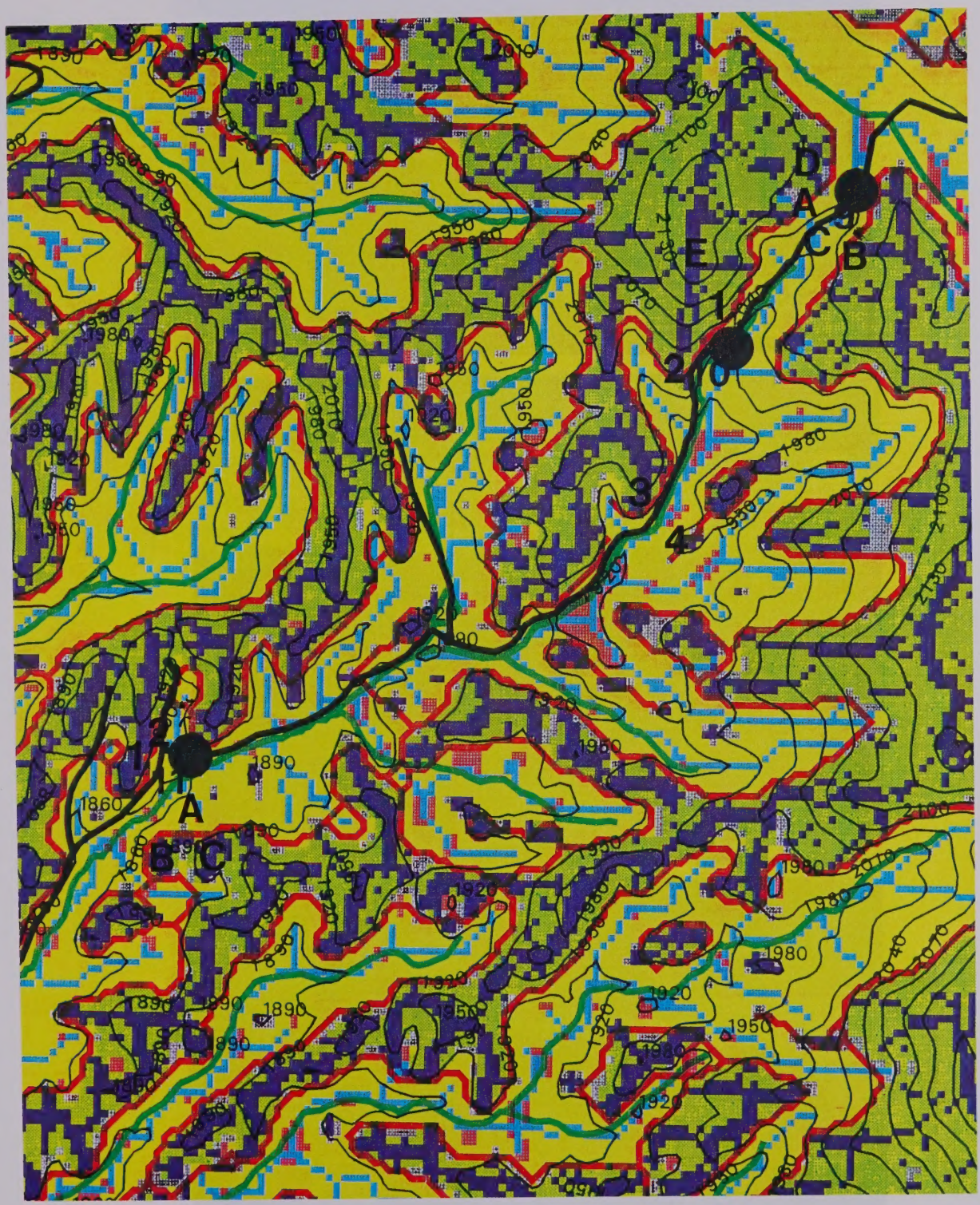



**Figure 10.** A close-up of the generalized hillslope morphology map for Red Rock Canyon quadrangle showing GPS locations where photographs of the landscape were taken.

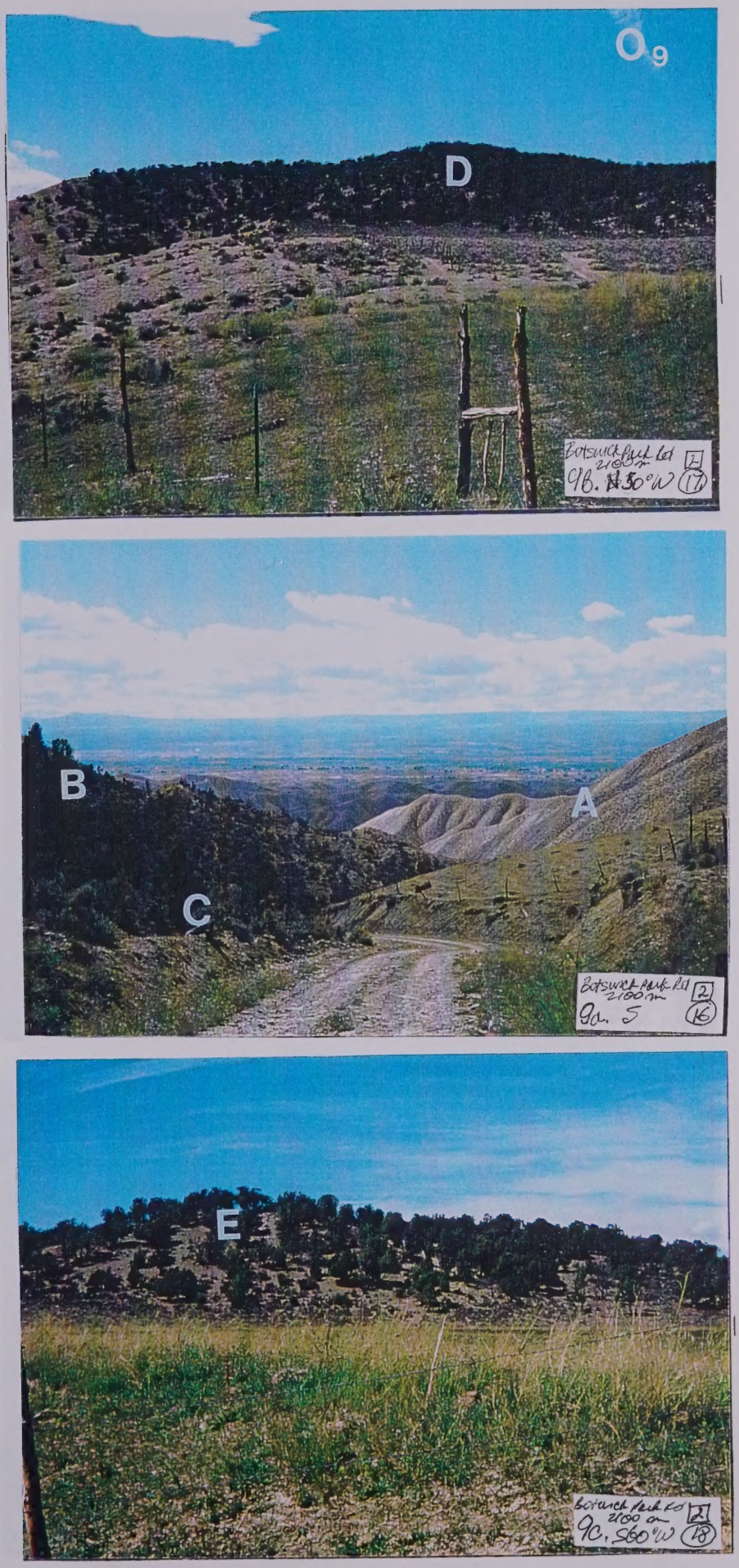



**Figure 11.** Three photographs of the area around GPS point 9.

**Figure 12.** Three photographs of the area around GPS location 10.

**Figure 13.** Three photographs of the area around GPS location 11.

## 3. Hillslope sediments and processes

Hillslope sediments are the materials derived from erosional processes taking place upslope (Kleiss, 1970). They are the same age as the alluvium they merge into at the foot or toe slopes (Walker, 1962a) Hillslope erosional processes include sheet and rill erosion, gully erosion, channel erosion, subsurface tunnel erosion through the processes of solution and piping, soil creep, and various types of mud or debris flows. Most of these processes are related not only to the intensity and volume of rainfall or composition of the soil material, but the shape of terrain also has direct effect on them. Various models exist for analysis and prediction of the effects of these erosional processes because their magnitude can be directly correlated with degeneration of landscape health through loss of soil productivity, salinization of soils, siltation of streams and rivers, and other effects. Thus for example the Revised Universal Soil Loss Equation (RUSLE) (Wischmeier and Smith, 1978; Renard et al., 1997) includes a terrain factor which combines two variables of hillslope morphometry, slope gradient and slope length, in an empirically derived equation.

Slope gradient measurements seem relatively simple, but they are not because usually there are several methods for deriving them. For example the Bureau's old GIS system MOSS/MAPS permitted four different methods for determining slope gradient from DEM data: the maximum, the minimum, the average, and the vector sum slope gradient analysis. All the techniques depended on calculating slope values between the center cell and the adjacent cells of a 3 x 3 cell neighborhood, but each of them produced somewhat different results. The ARC/INFO GIS has one basic technique which calculates the maximum slope gradient within a 3 x 3 neighborhood, and a similar method combined with its curvature function. Additionally, the author of this report obtained from the USGS an AML which calculates slope gradients along the flow direction paths calculated by ARC hydrologic terrain analysis functions. Figures 14 and 15 show a slope class map for the Red Rock Canyon quadrangle in Colorado.

Increase in the gradient of slope is causally connected to increase in velocity of water flow across the surface of the landscape as well as its carrying capacity. It is also related to increased probability of mass wasting in form of mudfalls or rockfalls. Slope length is an even more difficult property to clearly determine. Wischmeier and Smith (1978) defined it as the distance of movement of water and the particles it carries from top of the slope to a

Slope class map, Red Rock Canyond quad., Colorado

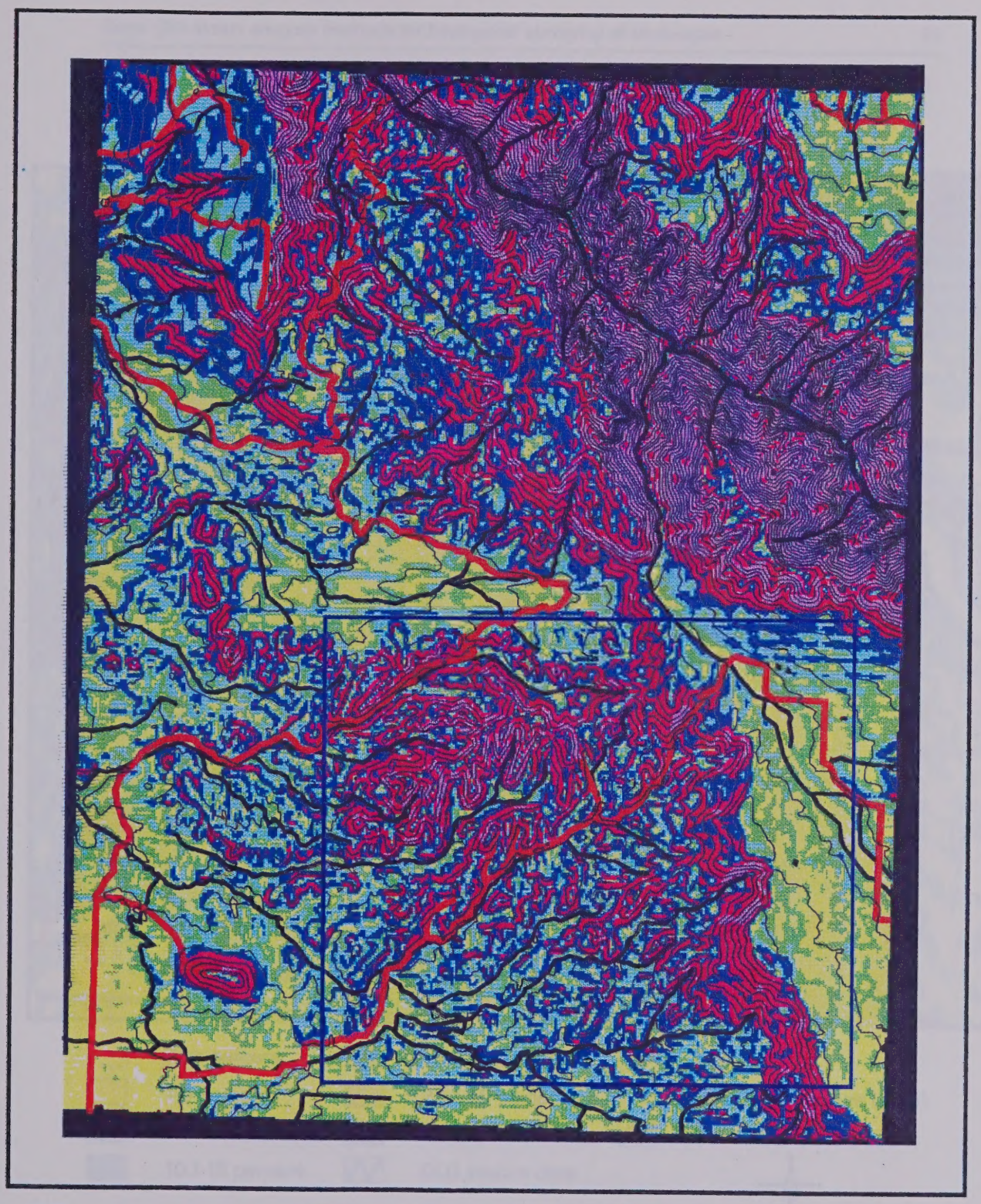



**Figure 14.** Slope class map.

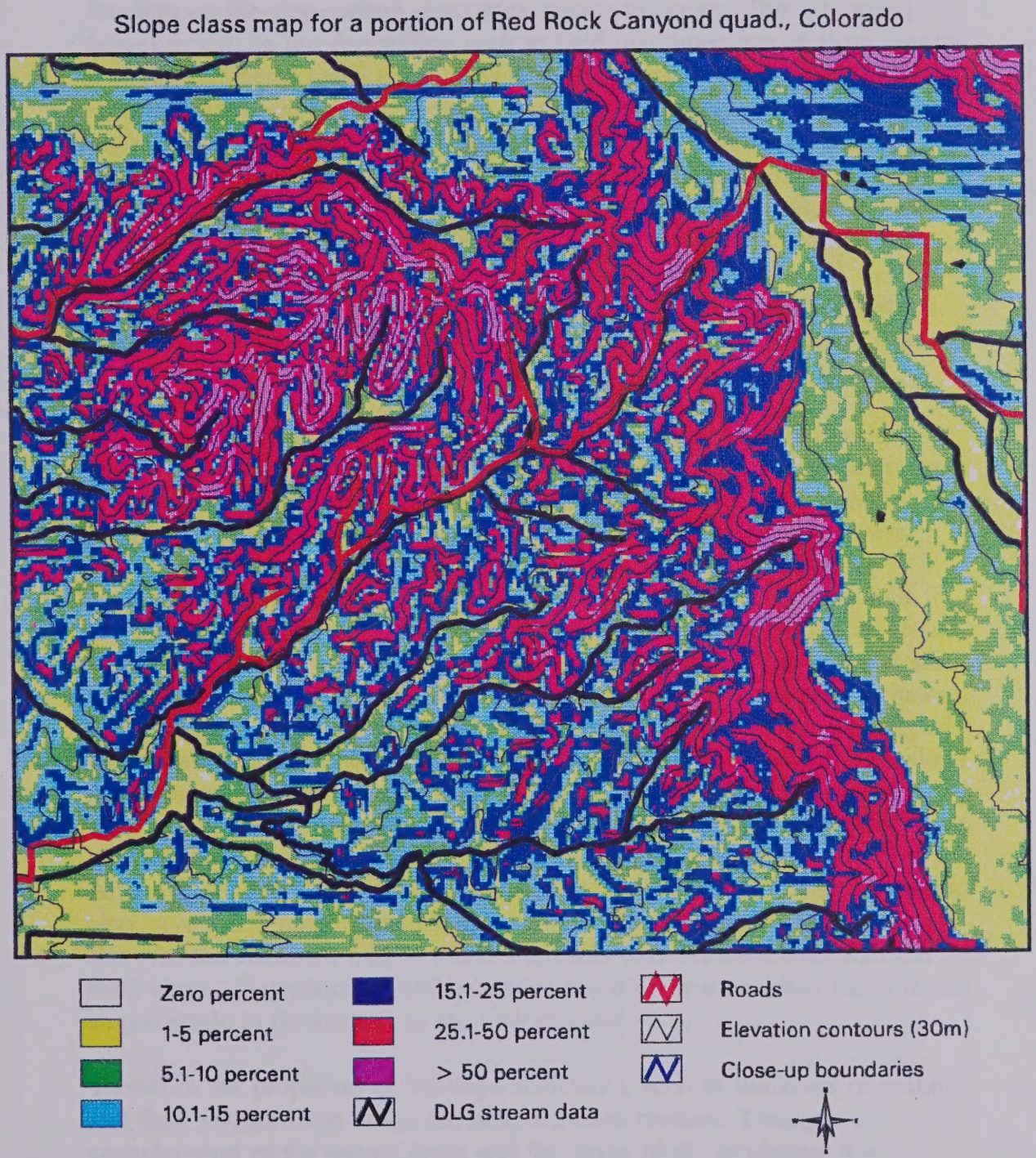



Figure 15. A section of a slope-class map.

location on the slope where deposition begins to occur. This definition, however, can be too demanding both in field measurements of slope lengths and measurements made from maps. Obviously flow can be stopped by all sorts of micro-relief, particularly in areas where slope gradient is not very high. The ARC/GRID GIS processing definition is that it is a distance upstream (to nearest divide or local elevation maximum) from any point on the landscape, or downstream (from the nearest divide or local elevation maximum) to any point on the landscape. Since these two distances are essentially the same they are probably differentiated purely to aid conceptualization of flow across the landscape. Figure 16 and 17 show a slope length map created using ARC/INFO commands showing the distance upstream from any point on the map.

Hillslope sediments and some of their properties, such as bulk density, percentage of clay and thickness of sediment, generally increase downslope, changing with distance of transport, or distance from the local summit which has been defined as slope length. The amount of erosion is very much dependent on which category of slope is being looked at. For example, hillslope material can be found in most head slopes with their convergent flow and on some linear slopes, but are absent or thin on nose slopes with their divergent flow and the upper portions of the linear slopes. Convex surfaces are mostly erosive, permitting little deposition of sediment, while concave surfaces are mostly depositional. The most severely eroded areas are the nose slopes, steeper linear slopes, and some head or foot slope positions where flow concentrates (Moore & Burch, 1986; Moore et al., 1986). Laboratory research shows that sediment movement is highest in the concave head slopes and lowest on the nose slopes (Schumm et al., 1987). Although sediment movement is highest on the head slopes, these positions also have thick mantles of hillslope sediment (Ruhe et al., 1967). Erosion removes the sediment mantle when a channel trenches headward into the head slope. Deposition reestablishes the sediment mantle when the adjacent slopes grade to the bottom of the new channel.

Therefore the properties of hillslope sediments, such as thickness or texture, and their relationships to the landscape are not random. Through consideration of the source areas and the shape of the landscape it is possible to predict the properties of this material with high degree of accuracy. Figure 18 illustrates hillslope sediments in profile from studies performed by Walker (1966). The particle size and composition of hillslope materials, soils and colluvium, depends upon the material found within the

Slope length map, Red Rock Canyond quad., Colorado

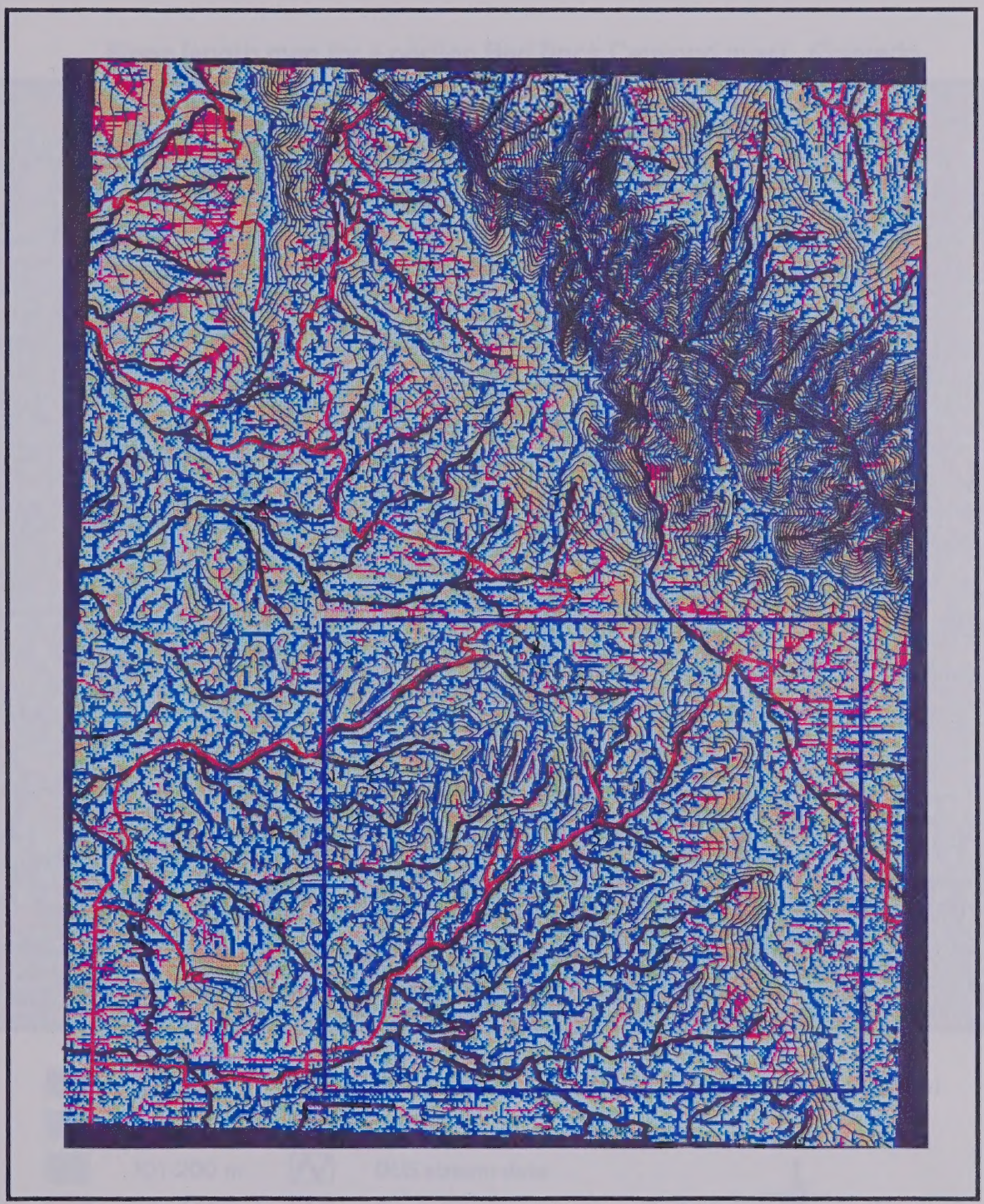



Figure 16. A slope length map.

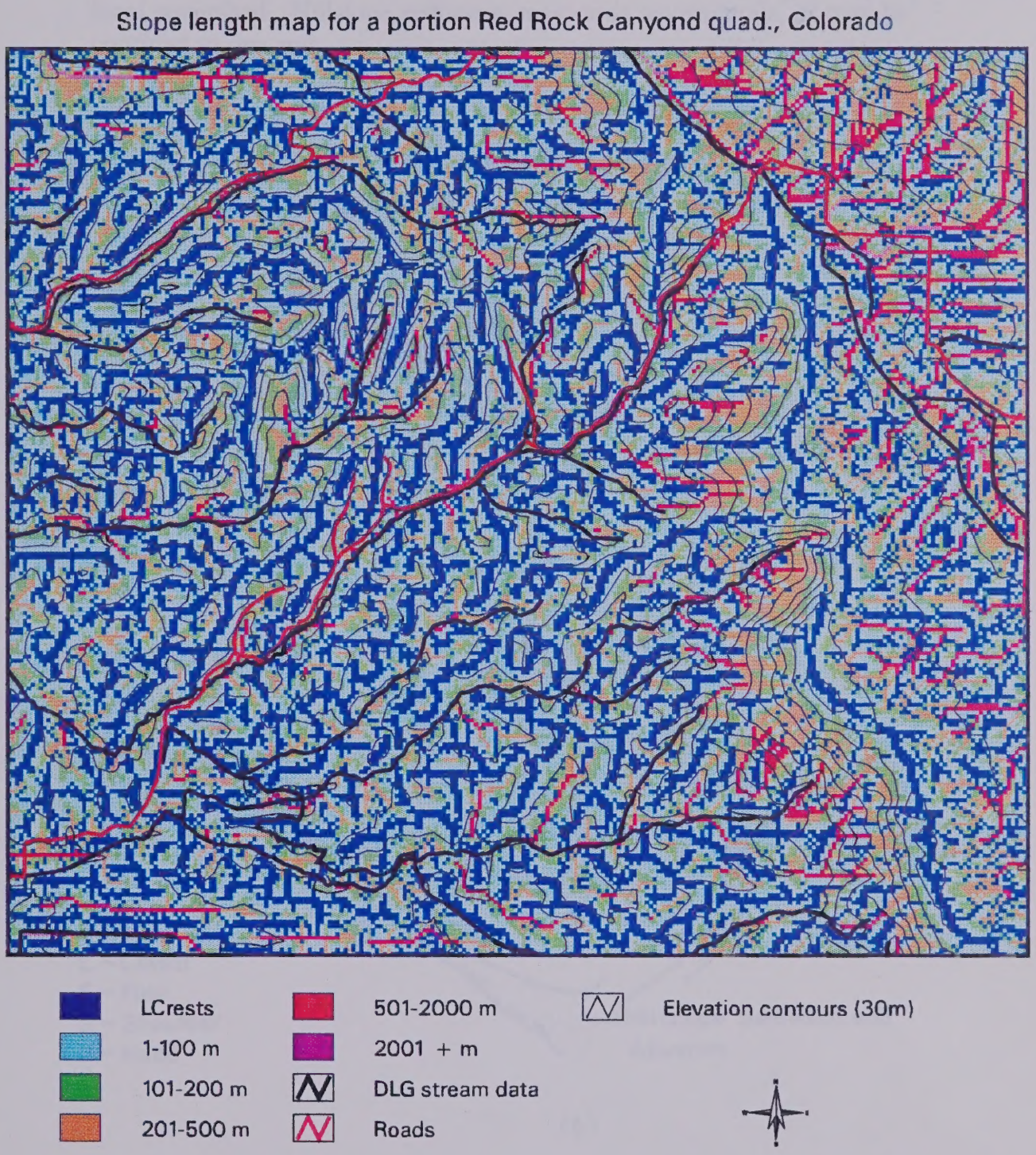



Figure 17. A section of a slope length map.

local watershed. Hillslope sediments may cross several soils, or may be confined to one soil.

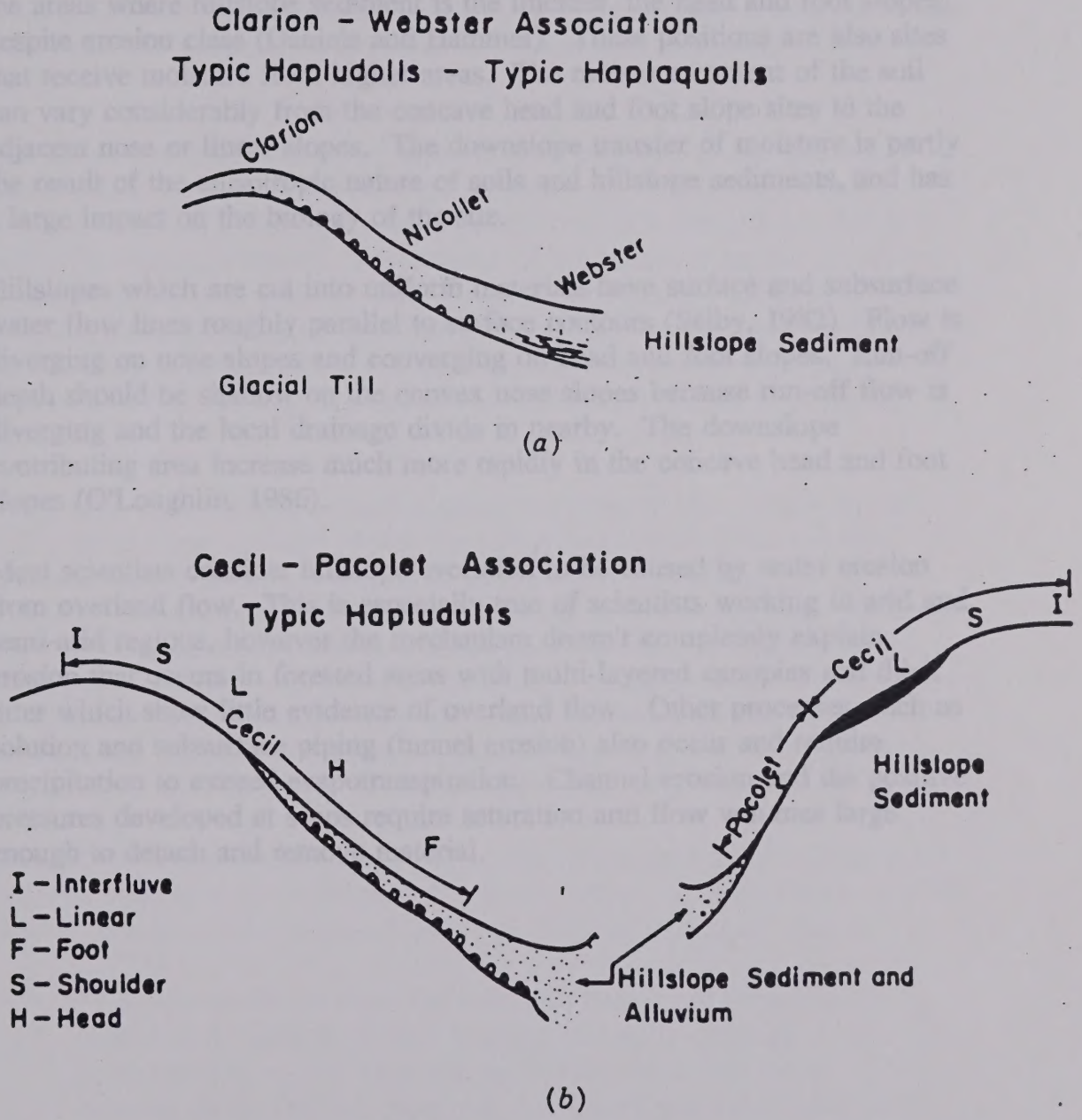
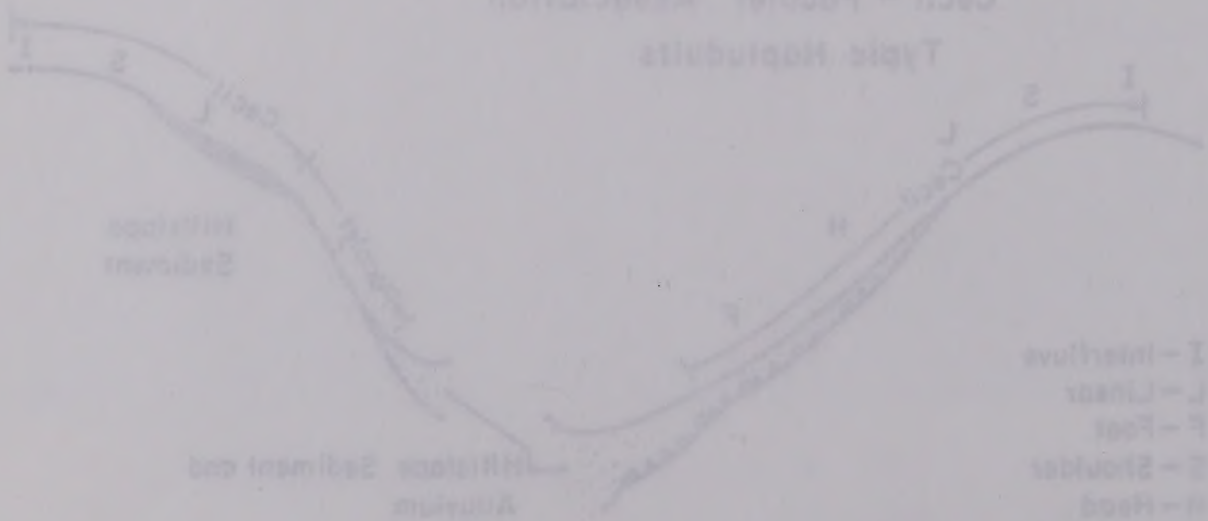



Figure 18. Thickness and landscape relationships of hillslope sediments and soils (Walker, 1966).



Soil moisture deficits are also affected by topography. The deficits generally decrease from the back slope to the foot slope to the toe slope (Butler et al, 1986). This has been observed by how landscape position influences where the grain yields of corn are highest, which appears to be the areas where hillslope sediment is the thickest, the head and foot slopes, despite erosion class (Daniels and Hammer). These positions are also sites that receive moisture from higher areas. The moisture content of the soil can vary considerably from the concave head and foot slope sites to the adjacent nose or linear slopes. The downslope transfer of moisture is partly the result of the anisotropic nature of soils and hillslope sediments, and has a large impact on the biology of the site.

Hillslopes which are cut into uniform materials have surface and subsurface water flow lines roughly parallel to surface contours (Selby, 1982). Flow is diverging on nose slopes and converging on head and foot slopes. Run-off depth should be shallow on the convex nose slopes because run-off flow is diverging and the local drainage divide in nearby. The downslope contributing area increase much more rapidly in the concave head and foot slopes (O'Loughlin, 1986).

Most scientists consider hillslope evolution to be caused by water erosion from overland flow. This is especially true of scientists working in arid and semi-arid regions, however the mechanism doesn't completely explain erosion that occurs in forested areas with multi-layered canopies and thick litter which show little evidence of overland flow. Other processes, such as solution and subsurface piping (tunnel erosion) also occur and require precipitation to exceed evapotranspiration. Channel erosion and the positive pressures developed at seeps require saturation and flow volumes large enough to detach and remove material.

## 4. Hillslope relationships within drainage basins

"Traditional studies of catenas have tended to examine single slope profiles but, with the aid of the computer, a large number of slope profiles can be handled at one time enables the sampling design to consider whole drainage basins and the variability within them of slope form and soils." (Gerrard, 1992)

The above quote reflects a very important point which is that hillslopes occur within the further morphologic arrangement of landscape form to accommodate the hydrologic processes that helped to form them, that is within the drainage basins. The concept of the catena is similar to the concepts of facies in geology, and related to the hillslope model in hydrology and geomorphology. Catenas describe "the interaction of soils and landforms, and therefore soil processes and geomorphic processes" (Gerrard, 1992), viewing that interaction primarily in terms of a hillslope profile.

Dalrymple, et al. (1968), created a generalized model of a hillslope and valley floor cross-sectional profile by trying to include all the possible elements of soil formation related to terrain relief, including erosion, transport, and deposition. Only some portions of the model might fit into any particular landscape, and few landscapes are likely to contain all the segments of it. Dalrymple breaks the profile into nine elements as described in figure 19. The figure shows predominant processes occurring on the hypothetical hillslope as related to different locations and different slope angles of the hillslopes, and includes direction of water flow on the slopes.

Gerrard (1992) does an excellent job of describing how the distribution of different soils in a catena is related to their position on the hillslope, and the flow regime at various stages of hillslope. Quoting him again directly:

> "The differences between the soils of a catena are generally related to differences in their position and their drainage characteristics so that emphasis is placed on the difference between freely drained upper parts of slopes and imperfectly to poorly drained lower portions. This provides a continuum between those sites where the influence of soil moisture is at minimum and those sites where maximum influence of soil moisture is felt. Slope steepness is one of the most important

factors that causes a variation in soil moisture conditions as steeper angles reduce the amount of water percolating through the soil and increase the removal, perhaps through accelerated erosion, of the upper portion of the soil profile. The essential feature is that soils can and do move downslope. For these processes to have their greatest effect the ground surface must slope downward continuously **from the crest to the base of the slope**, and it is incorrect to apply the term catena to landforms which lack this feature. " (Gerrard, 1992)

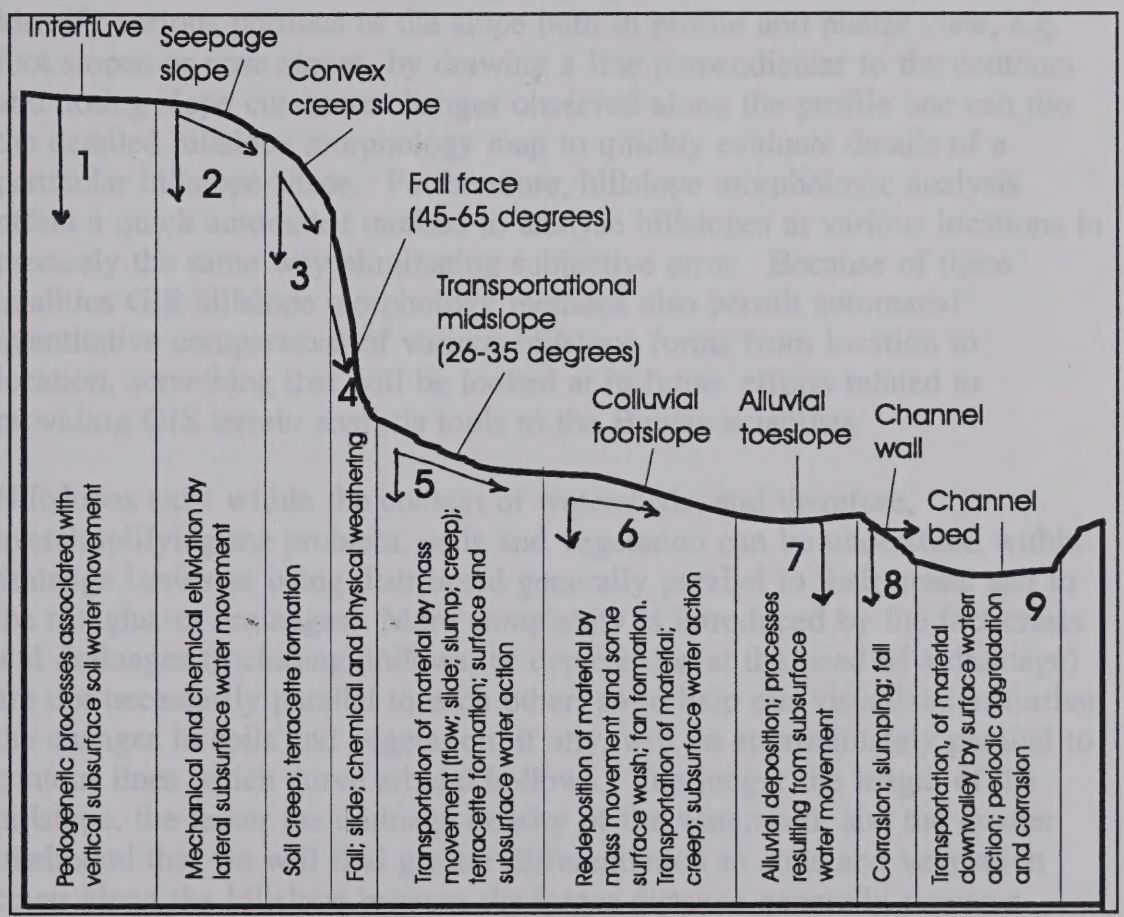
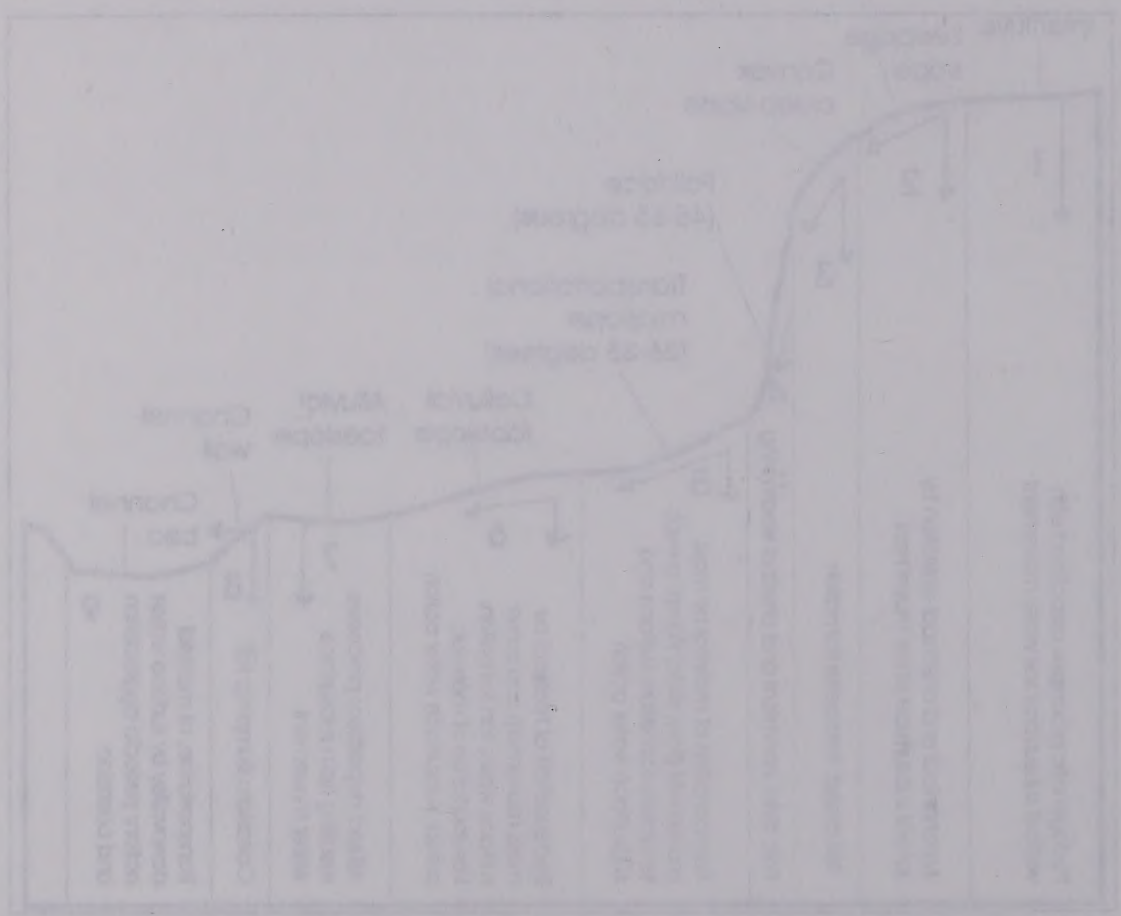

Interfluve
Seepage slope
Convex creep slope
Fall face (45-65 degrees)
Transportational midslope (26-35 degrees)
Colluvial footslope
Alluvial toeslope
Channel wall
Channel bed
1
2
3
4
5
6
7
8
9
Pedogenetic processes associated with vertical subsurface soil water movement
Mechanical and chemical eluviation by lateral subsurface water movement
Soil creep; terracette formation
Fall; slide; chemical and physical weathering
Transportation of material by mass movement (flow; slide; slump; creep); terracette formation; surface and subsurface water action
Redeposition of material by mass movement and some surface wash; fan formation. Transportation of material; creep; subsurface water action
Alluvial deposition; processes resulting from subsurface water movement
Corrasion; slumping; fall
Transportation, of material downvalley by surface water action; periodic aggradation and corrasion

**Figure 19.** Hypothetical nine-unit landsurface model (from Dalrymple, et al., 1968)

The hillslope morphology map could be understood as providing a map view of the hillslopes and other landscape features. The same thing could be said about an elevation contour map, however in the hillslope map



important aspects of the vertical order of the landforms are broken out, namely the crests, upper convex slopes, lower concave slopes, and troughs. The map therefore should be viewed as an aid in interpreting elevation contour data in terms of hillslope properties.

The detailed map can serve the quickly analyze slope facets to the level of resolution offered by the elevation data. The generalized map shows the general pattern of convex and concave slopes, and thus offers analysis of landscape that has been "smoothed" so that only the major feature relationships are seen. While the generalized data can offer a quick way to identify various portions of the slope both in profile and planar view, e.g. foot slopes or nose slopes, by drawing a line perpendicular to the contours and noting slope curvature changes observed along the profile one can use the detailed hillslope morphology map to quickly evaluate details of a particular hillslope shape. Furthermore, hillslope morphologic analysis offers a quick automated method to analyse hillslopes at various locations in precisely the same way eliminating subjective error. Because of these qualities GIS hillslope morphology methods also permit automated quantitative comparisons of various hillslope forms from location to location, something that will be looked at in future efforts related to providing GIS terrain analysis tools to the Bureau scientists.

Hillslopes exist within the context of watersheds, and therefore, oversimplifying the problem, soils and vegetation can be understood within drainage basins as being distributed generally parallel to their crests and to the troughs, or drainages. More complexity is introduced by the fact crests and drainages (including hollows, or depressions at the head of a drainage) are not necessarily parallel to each other, so to help our visualization further the changes in soils and vegetation, if any, will be approximately parallel to contour lines which curve around hollows. The longer the length of the hillslope, the lesser the drainage density of the watershed, and the greater likelihood that we will find greater differentiation in soils and vegetation cover along the hillslope because the larger distance generally prevents quick transport of sediments along the profile.

Changes in soil and vegetation pattern are also related to changes in slope gradient of the hillslope surface. In some locations disturbances of the surface through mass wasting occur producing breaks in the patterns. The basic difference between the types of patterns in soil and vegetation cover in the landscape is that some are produced by limitation of a resource, such as

water or a nutrient, or an extreme amount of a limiting resource, such as salt in soil, and that some are produced by disturbances occurring on the surface through mass wasting, but also through other disasters, such as a fire which usually destroys most of the vegetation cover. The types of soil and vegetation cover are also strongly influenced by the distribution of surface and subsurface water and the ground water table, locations of which can be inferred from elevation maps. One such map that can be created from elevation data is the flow accumulation map shown in figure 20 for the entire USGS quadrangle, and in greater detail in figure 21.

The flow accumulation map can be derived from a flow direction map made from a Digital Elevation Model. The flow direction analysis algorithm determines flow directions across the entire landscape based on the DEM data. The flow accumulation algorithm then calculates for each cell of the map how many other cells are draining into it. Selecting for ranges of flow accumulation values results in delineation of drainage network patterns, since flow on the landscape tends to concentrate into streams. Most of the locations outside of delineated drainage patterns are hillslopes and crests of hillslopes. Crests are identified by having a flow accumulation value of zero. Beyond that flow accumulation values tend to remain low until they begin to form a clearly defined drainage. Large increases of flow accumulation values within drainage patterns are due to junction of the channel with subsidiary streams entering it and bringing their own accumulated flow.

The flow accumulation map provides a clear and, in hilly or mountainous areas, mostly accurate picture of the distribution of surface water on the landscape. Although the resolution of the DEMs doesn't permit precise delineation of flow directions, at least the flow accumulation modeling process permits identification of the general flow patterns which can be verified by comparing modeled flows to other types of stream data, for example hydrography data available from the USGS in their Digital Line Graph format. Since subsurface flow generally tends to follow surface flow, the flow accumulation map also gives an imperfect image of the likely subsurface flow directions and concentrations. If a soils map is already available for the area it can be used to determine likely holding capacity and permeability to provide a more complete picture of subsurface flow. Furthermore, in dependence of local geology, groundwater generally follows terrain shape, and the flow accumulation map together with the original

Flow accumulation map, Red Rock Canyon quadrangle, Colorado

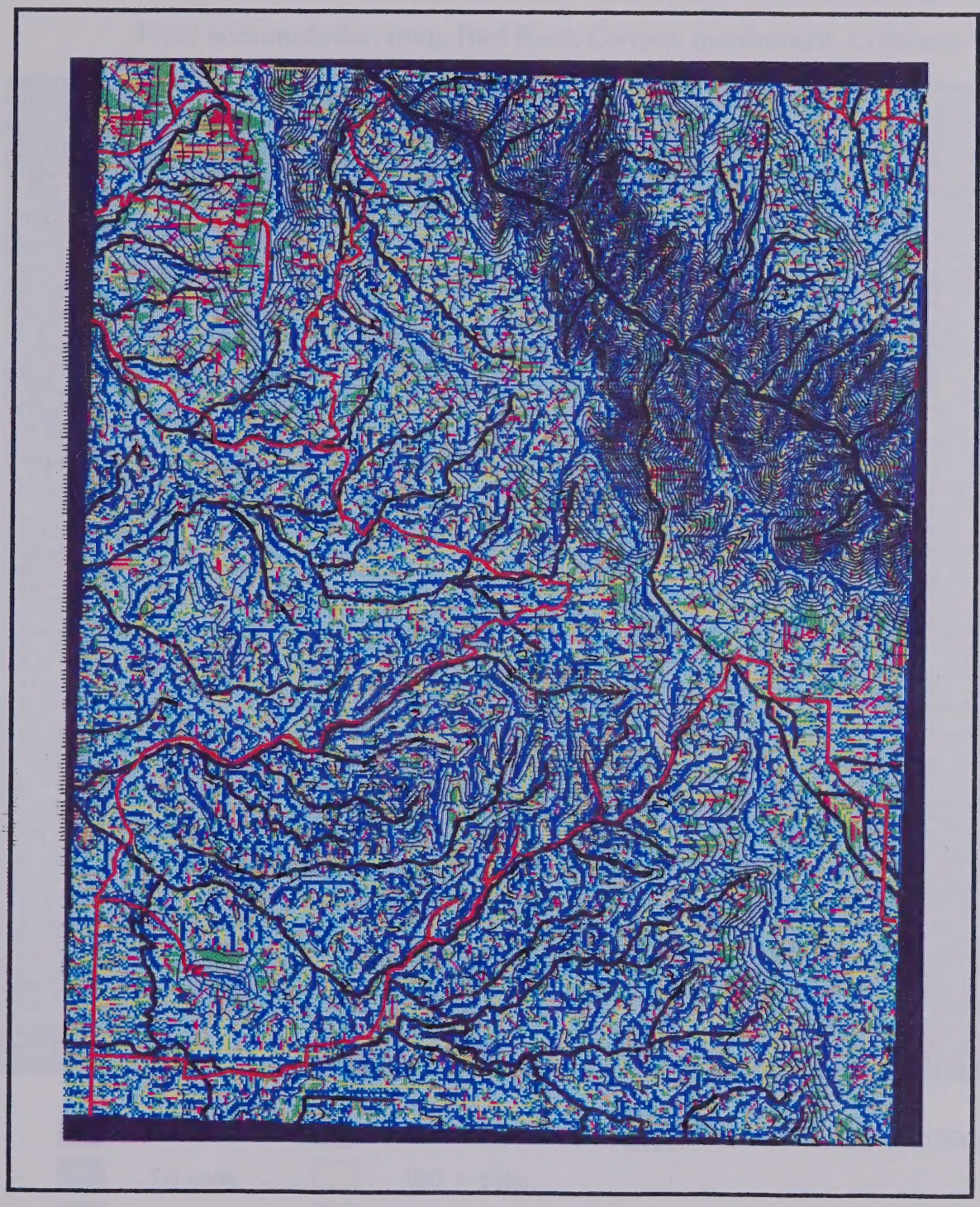



**Figure 20.** Flow accumulation map for the Red Rock Canyon quadrangle.

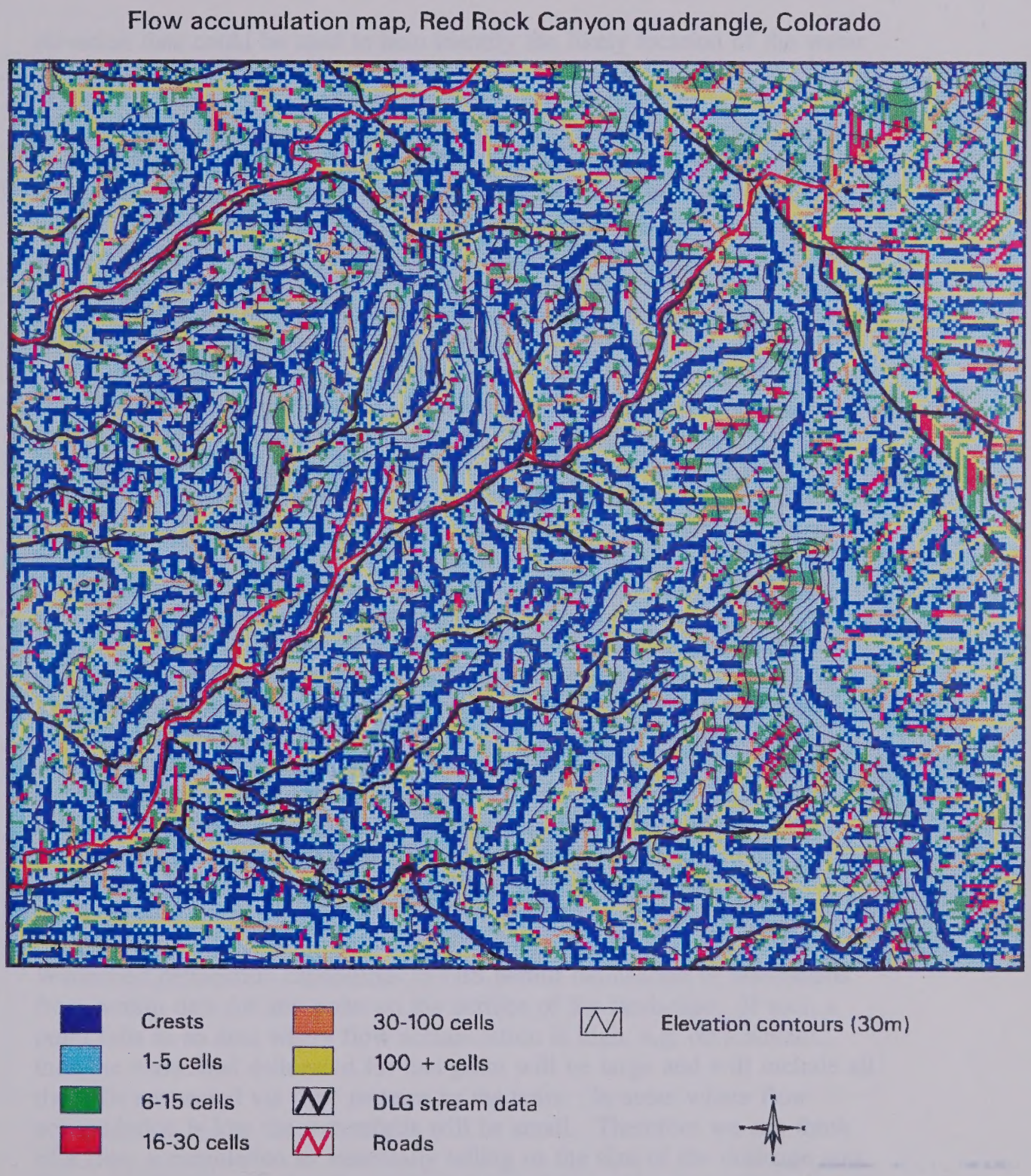



**Figure 21.** A close-up of a flow accumulation map.

elevation data could be used to help identify the likely location of the water table in absence of other data.

The soils and vegetation located in the drainage valleys is generally fluvial and riparian in nature, and influence of hillslope sediments ends at the point of their deposition. In some locations the slopes are short and steep and hillslope sediments predominate, while in other locations a valley has a chance to develop which consists mainly of fluvial sediments. Where this occurs depends on local geology and hydrology which influence the shape of the landscape through formative and erosional processes. Furthermore, within many drainage basins wetland areas can develop within concavities or areas of internal drainage in the landscape. All of the landscape features are related to the overall pattern of erosion and sedimentation processes that occur at various rates in different portions of the drainage basin depending on the shape of the land. Ultimately the eroded sediment and it's organic matter content, unless retained in a concavity within the drainage basin, will enter the drainage network and be carried out of the watershed.

Geographic Information Systems, such as ARC/INFO, contain functions which permit determination of watersheds in several ways. A good description and explanation of the flow path and watershed delineation process and some other related surface hydrologic analysis commands is available on request from the author and is entitled "An applications guide to surface hydrologic terrain analysis in ARC/INFO". A product of GIS watershed delineation methodology is illustrated in figure 22, which shows broad watersheds within the quadrangle, and then small mini-watersheds nested within them. Figure 23 shows the same information but in three dimensions and for a portion of another quadrangle. It also includes generalized hillslope morphology classes as the background to the watersheds.

Watershed delineation capabilities in GIS permit delineation of watersheds from terrain data for any point on the surface of the landscape. If such a point falls in an area where flow accumulation is high, e.g. on a stream, then the watershed delineated for that point will be large and will include all the cells connected via flow patterns to the point. In areas where flow accumulation is low the watersheds will be small. Therefore we can think of a flow accumulation as essentially telling us the size of the drainage area for any particular cell, but the size is expressed in numbers of cells rather than in area units, a conversion that is easy to make if we consider

Watersheds and sub-watersheds, Red Rock Canyond quad., Colorado

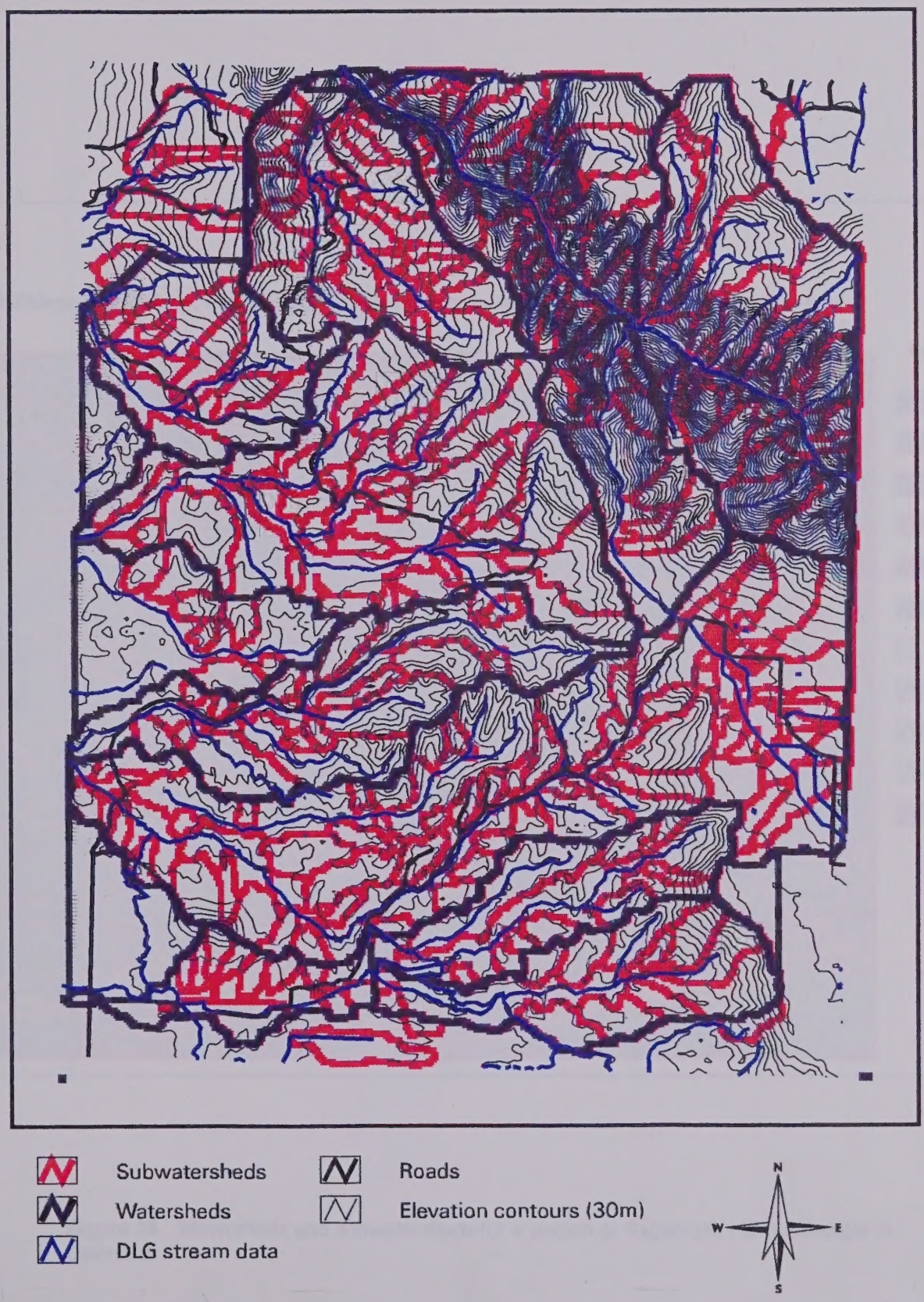



**Figure 22.** Watersheds and subwatersheds delineated using ARC/INFO surface hydrologic terrain analysis capabilities.

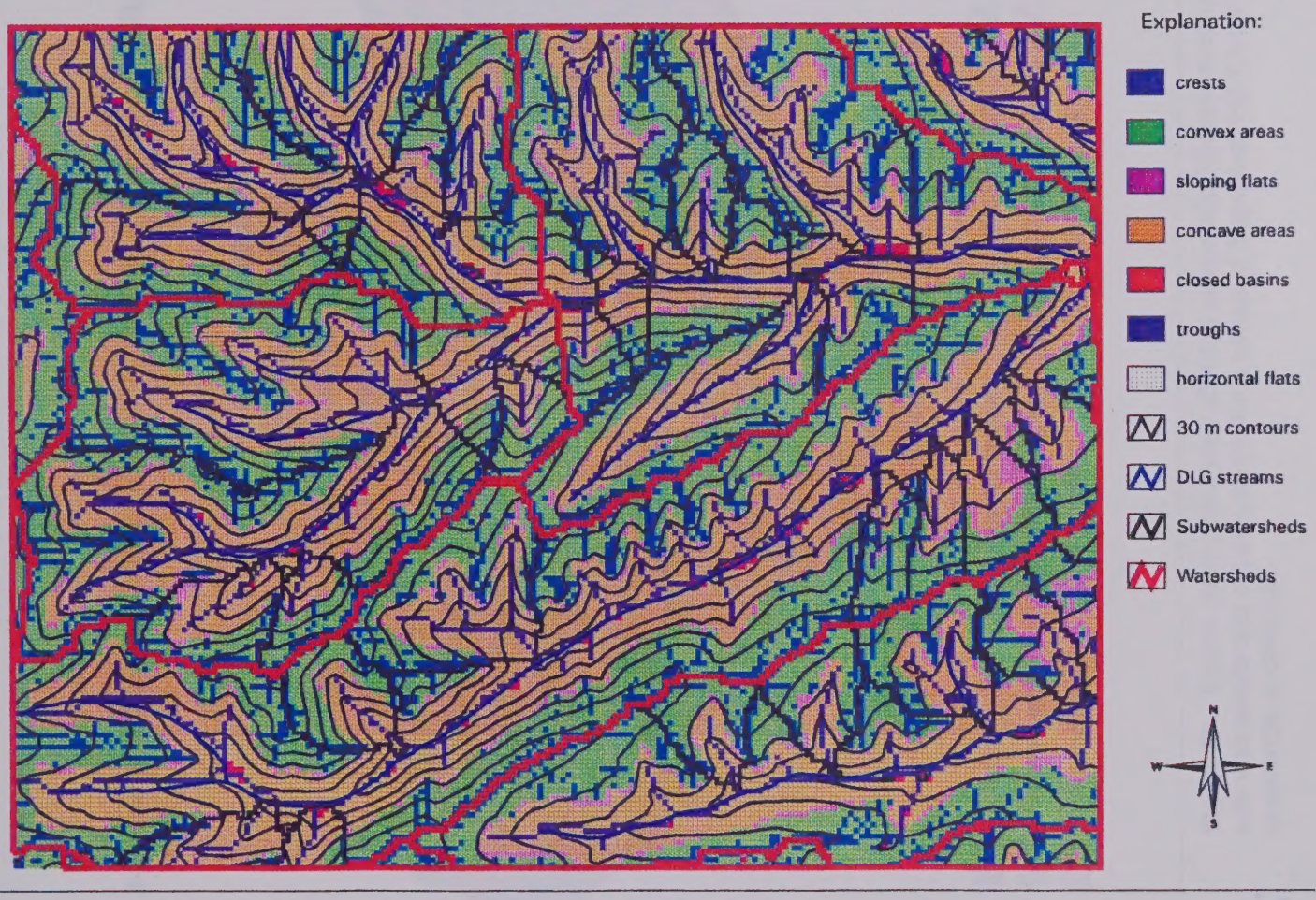



**Figure 23.** Watersheds and subwatersheds for a portion of Sagebrush Hill quadrangle in Colorado.

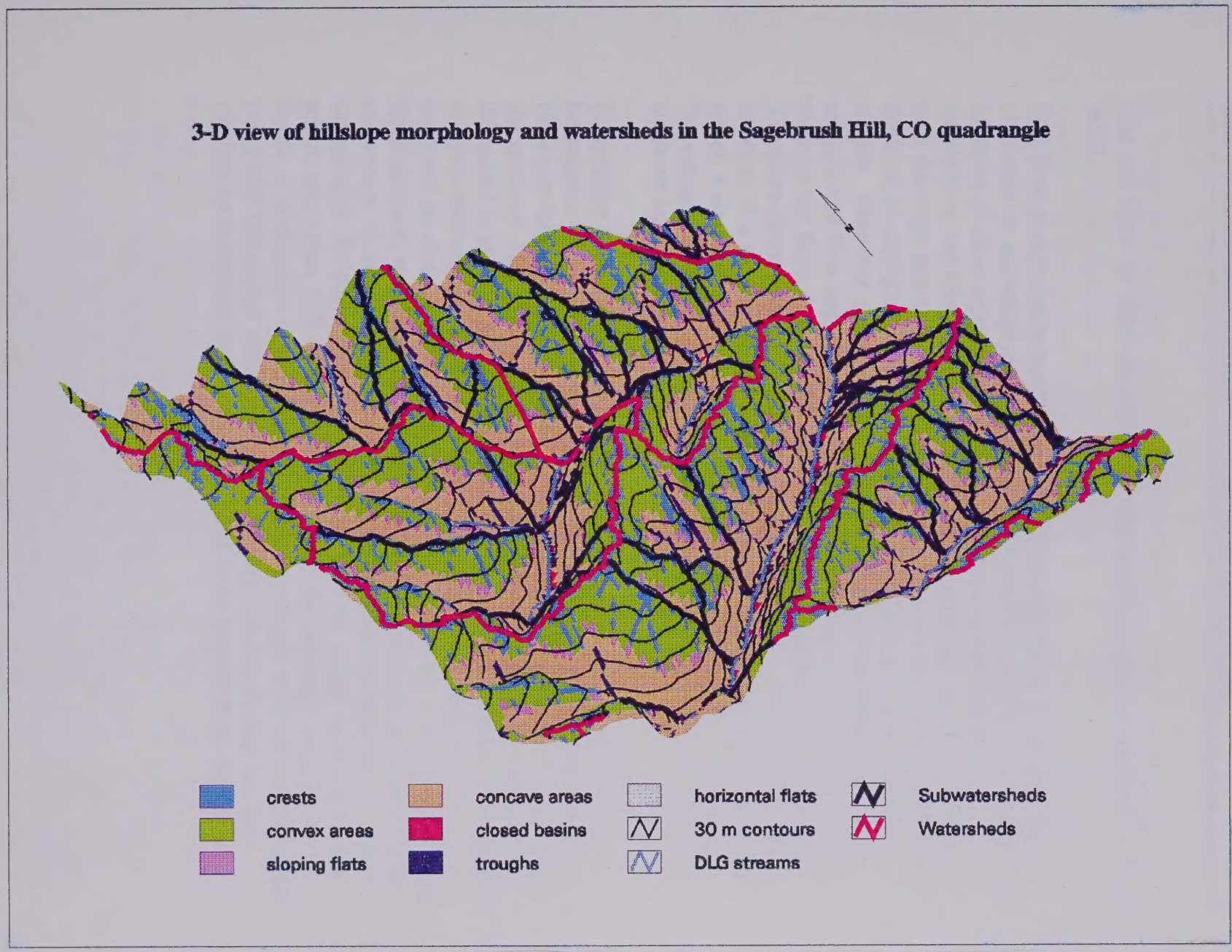



**Figure 24.** A three dimensional view showing generalized hillslope morphology together with watersheds and subwatersheds for a portion of Sagebrush Hill 7.5-min USGS quadrangle in Colorado.

that one 30m- by 30m-cell covers an area approximately equivalent to .224 acres.

GIS flow accumulation modeling from DEM data helps to explain the emphasis on statistical understanding of a basin in terms of flow rather than in terms of clear topographic divides. GIS watershed delineation capabilities can identify a watershed for each drainage juncture up to the next drainage juncture. Therefore we can get watersheds that include only portions of contiguous hillslope segments that drain into a segment of a stream. However a case can be made that, if elevation data are accurate enough and flow approximately follows the directions determined from it, most of the flow, at least 85% remains within the delineated boundaries. Therefore there exists a "virtual topographic divide" related more to the location of a section of a hillslope with respect to the stream segment into which it drains than to any clear "actual topographic divide". The term "topographic" still applies because the separation of flow is related to the shape of land surface.

In actuality there will be some flow between the locations on the very boundaries of delineated areas unless a clear topographic divide is present. However for a delineated watershed large enough this flow will not exceed the arbitrary 15% limit, and for systems analysis purposes (which will be discussed in another publication) we can still treat each delineated watershed or mini-watershed as an independent open system unit even if it is not bordered by clear actual topographic divides. However, if the boundaries of the delineated watershed are complex and sinuous enough to locate a large percentage of the watershed area near the delineated boundaries, and clear topographic divides cannot be ascertained, then we might have a situation where more than 15% of the flow is between the adjacent watersheds. Again, this situation is probably not common enough to be of concern when using GIS delineated watersheds, although this conclusion has not been verified by empirical studies and will need to be looked at in the future.

## 5. Application of terrain maps in biophysical surveying

Terrain maps described in this report are easy to produce with Geographic Information Systems for large areas of the landscape. Insofar as terrain morphology has strong impact on ecosystem processes in mountainous or hilly areas, any information that we can use to map out diversity of the landscape is of tremendous importance, particularly if other data are scarce. Even in complete absence of any other data DEMs can provide us with information on terrain shape through various morphometric measurements. Since the morphology of hillslopes is very closely related to hillslope hydrology, the information we are obtaining tells us about the likely distribution of surface waters, soil moisture, and (with some reservations) also groundwater. Morphology of hillslopes and drainages in the area provides indications of local geology including the possible composition of the rock formation. For any particular location on a hillslope, the gradient of slope and distance from the nearest divide (slope length) are both significant with respect to the type of hillslope sediment we are likely to find. Location within concavity or convexity, on a crest, near a trough, or in an enclosed basin tells us something about whether the soils and the environment are primarily going to be erosional or depositional in nature. With terrain analysis information and knowledge of the general climate and elevation of a project area above sea level and location we should be able to predict at least some of the attributes of soils and vegetation that we are likely to find distributed throughout the landscape.

Working within the United States we rarely have to rely on topographic data alone and can make use of other information that together with terrain data can help us interpret the landscape in terms of soils, vegetation cover, habitats, and even ecosystems and their processes. With the availability of vegetation data from satellite imagery, the terrain data can help to explain the quantities and types of vegetation identified in the image in terms of shapes of the land as well as hydrologic connections between various portions of the landscape. The more data we have available, the more connections between environmental factors we can make, and the more creatively we can use terrain analysis to identify those components of ecological processes that is affected by landforms.

The most obvious ways that terrain analysis data can be used is as an aid in making of soil and vegetation surveys. Based on terrain maps, knowledge of hillslope sediments and processes, and knowledge of the study area a

preliminary map can be drawn or generated in GIS by a soil scientist or ecologist through interpretation of the likelihood of certain soil properties or moisture regimes from the various terrain analysis maps. Information obtained from other available data needs to be also included in the preparation of a preliminary map. Once clearly established, the methods and rules for overlaying themes to develop a preliminary soils and vegetation parameters map could be encoded into a cartographic model and automated using GIS.

From the terrain maps alone, based on curvature of the land, slope gradients, slope lengths, and hydrologic regimes, one should be able to identify different slope types or hillslope sections such as head slopes, nose slopes, foot slopes, crests, and so forth. Based on this analysis it should be possible to predict at least in relative terms the magnitudes of related soil attributes likely to be found in these locations, such as sediment size, percentage of clay, thickness of sediment, and others. One could also try to predict the likely location of types of vegetation, for example riparian vegetation associated with streams or depressions on the land. Combining the terrain maps with geologic maps and satellite images classified for vegetation attributes should permit further verification of some of the assumptions made about soil and vegetation distribution on the basis of terrain data alone. With adequate data we should be able to put the jigsaw puzzle based on different issues related to terrain shape together according to logical concerns, and perhaps even be able to predict to a reasonable degree of accuracy the likely soil and vegetation types to be found in this or that particular section of the landscape. However complex our analysis gets and however many data sources it involves, terrain data will continue to serve as the source of information for resource scientists about the basic structure and processes related to the interconnections between various locations on the landscape.

The preliminary map should be based on all the data we can gain access to available for the project area or region. Once we have generated a preliminary map which shows us all the known environmental parameters (terrain and non-terrain) that might influence the amounts and types of soils and vegetation present in the project area, we can use the map to help us plan an intelligent sampling program to test our preliminary conclusions. Such an approach to planning of field sampling locations will be more accurate than a random approach, but we also have to be careful to try to

both verify, as well as challenge and test our interpretation of the landscape based on the maps.

After the field data has been collected and analyzed it is entered into the database, displayed on maps and compared using overlay and statistical methods with the predictions of the preliminary map. At this point it becomes possible to evaluate the accuracy of the original predictions, and to develop a final product by incorporating the new data into the survey maps. The benefits of using GIS in this process are several and include the following facts.

- We are thoroughly utilizing all the data available to us in developing a preliminary map (e.g. 7.5-min 30m DEMs which are available for most locations in the United States) which will help us plan a logical approach to field sampling.
- The more mechanical procedures in the model for using maps can be automated in GIS, while the procedures requiring user input can potentially be developed into an expert system of rules that works with the aid of GIS, permitting a more standardized evaluation approach to different landscapes
- The GIS permits us to apply various depths of analysis (in dependence of availability of data) to large areas of the landscape providing us with both qualitative and quantitative insight into ecosystem processes.
- The GIS provides tools to analyze the terrain in ways that cannot be done manually or would require too much labor input to perform correctly without help of computers.
- The GIS permits us to maintain a historical record of our data collection and analysis procedures so that we can retrace our steps for arriving at various conclusions at each step of the analysis process.

The product of the GIS based initial analysis of the project area, the preliminary survey map permits us to understand the spatial relationships between various environmental factors, including terrain morphology, so that we can develop a logical field sampling plan to confirm or to contradict our assumptions. The process of developing the preliminary map should also include a few reconnaissance style surveys of the project area to ground truth some aspects of the component maps. Since the knowledge used to create preliminary maps will be increased each time the procedure is performed, the model developed will be improved with each application.

## 6. GIS terrain analytic capabilities and documentation planned for the future.

The current document is meant to provide a cursory examination of GIS hillslope terrain analysis capabilities and their usefulness in the context of using geomorphic understanding for biophysical surveying of large areas of landscape. In hilly and mountainous areas terrain morphology has important influence on ecosystem processes. These influences could be summarized as follows. The shape of terrain:

- affects how irradiation by sunlight is distributed throughout the earth's surface (see figure 24 on the next page).
- complexly influences local atmospheric conditions to create microclimates;
- interacts with the overall climate of the region, e.g. change of climate with elevation;
- influences distribution of surface waters and therefore the availability of moisture and nutrients which are transported by streams;
- influences erosive-depositional processes that affect the condition of the substrate (looked from the viewpoint of hillslope, fluvial, and watershed geomorphology and involving mass wasting, soil erosion, and sediment yield).
- influences processes of evapotranspiration, subsurface water and groundwater recharge, and other processes related to watershed water and energy balance models;
- affects the processes of soil formation and disintegration and therefore soil type distribution and productivity.

As discussed in the introduction to this work, terrain morphology in hilly and mountainous areas can be divided into three interacting geomorphologic components. These components are the hillslopes, the drainages (channels, streams, rivers, even hollows), and the watersheds within which the other components occur. An appropriate way to study the effects of terrain morphology on ecosystems for large areas to develop ways of mapping and measurement of these components. Many such mapping and measurement methods have in fact already been developed in the context of developments in the sciences of geomorphology and hydrology.

Northern and southern facing slopes, Red Rock Canyond quad., Colorado

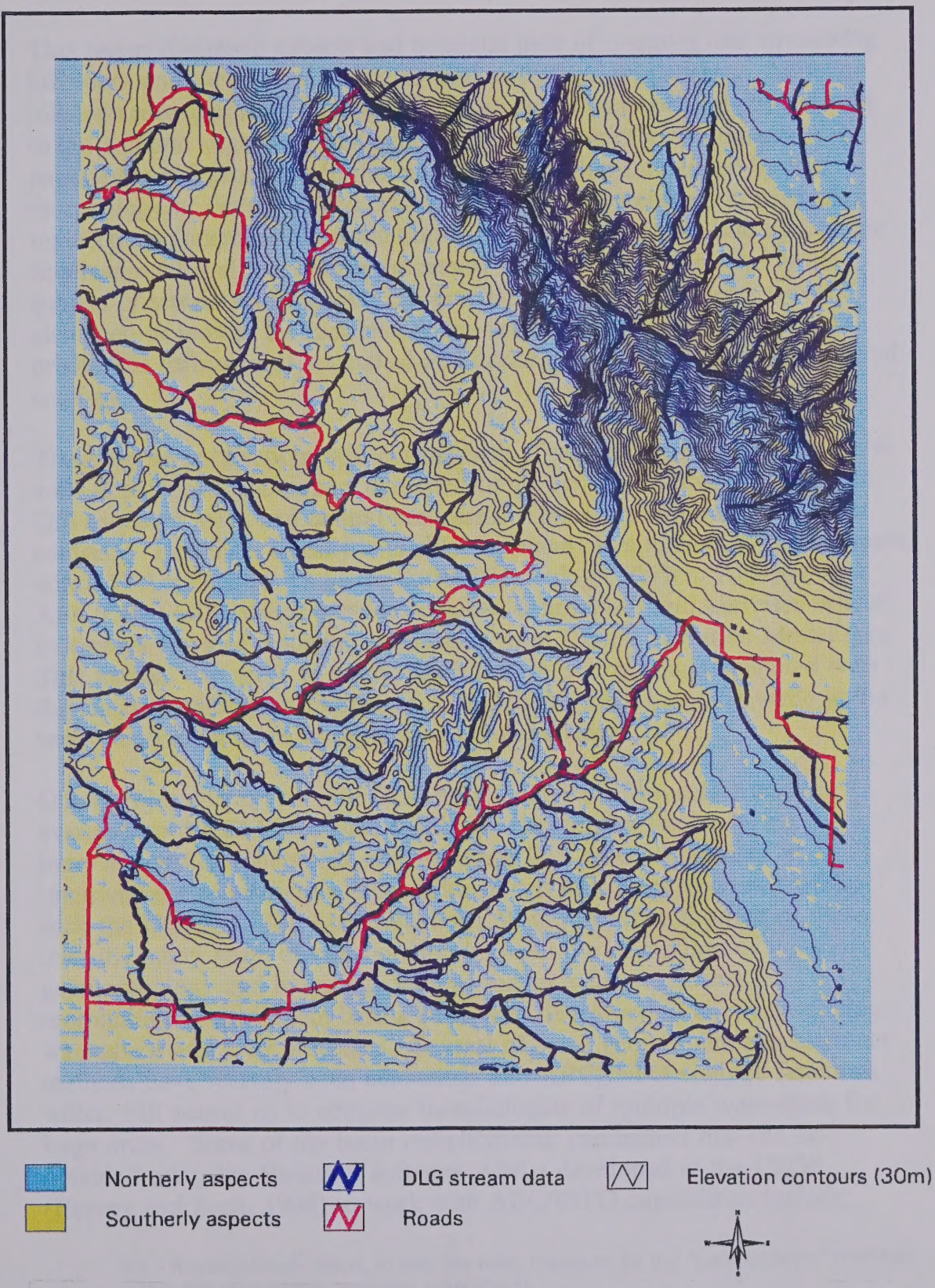



**Figure 25.** An aspect map classified into northerly and southerly aspects.

This report discussed aspects and potential uses of mapping and measuring hillslopes and their morphologic as well as hydrologic patterns. Although hillslope measurements represent the most direct ways of analyzing terrain to aid soil and vegetation mapping, the distribution of environmental parameters and processes in the landscape is further influenced by the morphology of drainages and drainage basins. A watershed, in particular, represents a fundamental terrain unit that has both landform and hydrologic implications for all ecosystem processes. Therefore to do justice to the subject of terrain analysis with Geographic Information Systems we will also need to look at the capabilities and uses of GIS to map, model, and predict the influence of watershed and drainage pattern morphology on local ecology.

These future publications will consist both of step-by-step user's manuals as well as technotes and papers that concentrate on the relationships between GIS modeled maps and natural processes. This report falls into the latter category. However, already available on request is a manual style document entitled "Applications Guide to Surface Hydrologic Terrain Analysis in ARC/INFO GIS" which provides detailed instructions and exercises related to various ways of modeling watersheds from Digital Elevation Model data. This manual can serve as an excellent first step in getting acquainted with the raster modeling capabilities of ARC/INFO's GRID module while at the same developing maps of immediate practical value.

Other projects involved with GIS terrain analysis will result in making available to the BLM resource specialists capabilities for analyzing the morphometry of watersheds, and for using GIS geomorphometry in improvement of predictive capabilities of soil erosion prediction models such the Universal Soil Loss Equation. With respect to the first of these, over the many years of collaboration between the disciplines of geomorphology and hydrology various methods for measuring the morphology of catchment basins have been developed to aid in describing watersheds and their processes. Several of these geomorphic measurement methods have recently been automated into ARC/INFO analytic functions which will permit us to compare morphologies of multiple watersheds for large areas. Some of the basin morphometric parameters that can be obtained using the Basinsoft software AMLs developed at the USGS (Harvey and Eash, 1996) to work with ARC/INFO capabilities include:

BS - Average basin slope, in feet per mile, measure by the "contour-band" method, within the contributing drainage area (CDA).

SF - Shape factor, dimensionless, ratio of basin length to effective basin width.

ER - Elongation ratio, dimensionless, ratio of (1) the diameter of a circle equal to that of the basin to (2) the length of the basin.

RB - Rotundity of basin, dimensionless.

CR - Compactness ratio, dimensionless, the ratio of the perimeter of the basin to the circumference of a circle of equal area.

RR - Relative relief, in feet per mile, the ratio of basin relief to basin perimeter.

MCS - Main channel slope, in feet per mile, an index of the slope of the main channel computed from the difference in streambed elevation at points 10 percent and 85 percent of the distances along the main channel from the basin outlet to the divide.

MCSR - Main channel sinuosity ratio, dimensionless, the ratio of main channel slope and basin length.

SD - Stream density in miles per square mile.

CCM - Constant of channel maintenance in square miles, or the area needed to maintain a mile of channels, and an inverse of stream density.

MCSP - Main channel slope proportion, dimension less.

RN - Ruggedness number, in feet per mile, a product of stream density and basin relief.

SR - Slope ratio of the main channel slope to basin slope, dimension less.

The watershed morphometric parameters will provide yet another way to describe morphology of the terrain, and methods for describing drainage pattern morphology are also currently being reviewed for application with GIS. Using watershed, drainage pattern, and hillslope morphometric techniques the BLM resource scientists will have access to a full suite of automated tools for making maps and measurements that describe landscape morphology and many aspects of it's hydrology. The tools can be used for analyzing more quantitatively than ever before the relationship of terrain to ecosystem processes, especially the physical processes of soil erosion, mass wasting, runoff, and flooding.

The second area of development will involve utilizing GIS geomorphometric capabilities to help improve models for analysis and prediction of sheet and rill erosion on landscapes. This project will utilize morphometric methods

very specifically to try to account for spatial variation in sheet and rill erosion as it relates to changes in landscape form. Improvements in soil erosion prediction technology for large areas would be extremely useful for analysis of potential environment impacts of various rangeland management approaches.

The results of both efforts will provide techniques that are directly utilizable by the field scientist to help them with biophysical surveying and ecosystem based management of public lands under their jurisdiction, and should help improve our understanding of how to manage our ecosystems as soundly as we can. The various methods and their uses described here and in other current or future works will be developed and provided based on interest and requests from BLM field offices. They represent one of the ways in which NARSC is taking existing advances in research and analysis techniques and making them available to the field for practical application. We hope that providing this information we will also be able to tap into your creativity and learn from your experience in using GIS as a scientific analysis tool.

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